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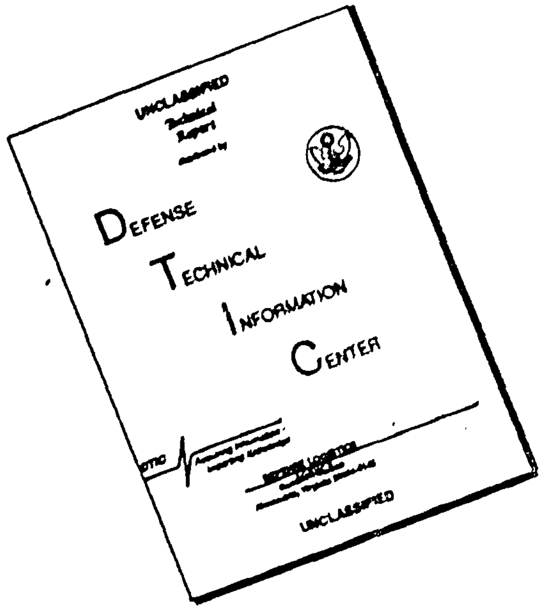

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WADD TECHNICAL REPORT 61-100

DEVELOPMENT OF STABLE, HIGH POWER, HIGH PRESSURE ARC AIR HEATERS FOR A HYPERSONIC WIND TUNNEL

R. C. ESCHENBACH
G. M. SKINNER
AND ARC LABORATORY STAFF

SPEEDWAY RESEARCH LABORATORY
LINDE COMPANY
DIVISION OF UNION CARBIDE CORPORATION

JULY 1961

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AERONAUTICAL SYSTEMS DIVISION

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DEPUTY FOR TEST AND SUPPORT
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AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report summarizes research on arc air heaters for wind tunnels conducted at the Speedway Research Laboratory, Linde Company, Union Carbide Corporation on Contract AF 33(616)-7205. The contract is a continuation of preceding Contract AF 33(616)-6271. Both contracts are segments of Task No. 13995, Project No. 1426. Work on Contract AF 33(616)-7205 was performed during the period from 1 June 1960 to 31 March 1961 by R. J. Baird, C. A. Hauck, R. J. Sarlitto, E. F. Stresino, D. Wizansky and the authors. The contract was initiated and monitored by the Directorate of Engineering Test, Deputy for Test and Support of the Aeronautical Systems Division with Mr. W. H. DeMent of the Aerodynamics Division, as task engineer.

ABSTRACT

Engineering research was performed on high voltage arc air heaters for hypersonic wind tunnels. Scaling laws and factors affecting them were established for the High Voltage arc air heater. Two arc heater designs, capable of operating at two and four megawatts, respectively, were constructed and tested. Satisfactory operation was achieved with both designs at minimum operating specifications of one megawatt power to the air, 500 psi stagnation pressure, greater than 50% efficiency, contamination less than 0.1% in the effluent air jet, and running times longer than one minute. A plenum chamber for dual operation of two 2 megawatt arc air heaters was designed, built and tested successfully. Heat losses in the plenum were less than 20% when operating at 200 psi pressure with 0.7 megawatt in the air effluent. The magnitude of irregularities in brightness of an atmospheric pressure jet from a High Voltage arc air heater ranged from 6 to 30% rms. Variations in Mach number across the core of a 1-inch diameter free jet in a small wind tunnel were less than $\pm$ 0.2 at Mach 5. Preliminary trials of alternating instead of direct current power were successful with the High Voltage arc air heater and unsuccessful with the Direct and Toroidal arc air heaters. Design and operating data were projected for High Voltage arc air heaters capable of operating at 40 and 100 megawatts of power with efficiencies of 50% or higher. The performance of three 40 megawatt heaters operating into a plenum chamber was also projected.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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I. INTRODUCTION

The requirements for air heaters for wind tunnels to be used for aerodynamic research are quite demanding. For example, the power flux necessary to simulate velocity and density in gliding re-entry within the flight corridor is about 1 megawatt per square foot of test section for velocities of 4000 to 20,000 ft/sec. Full simulation of free flight at altitudes near the lower limit of the flight corridor increases the necessary power flux to about 10 megawatts per square foot in the same range of velocities.

If simulation of Mach number as well as velocity and density is undertaken, impractically high air supply pressures are necessary to produce velocities above 12,000 feet per second. Considering a velocity of 20,000 feet per second at an altitude of 233,000 feet, true temperature simulation calls for an arc chamber pressure of 8800 atmospheres. However, a reduction in Mach number to 10, while retaining velocity and density simulation, permits a reduction in pressure to 230 atmospheres, a value now within the realm of possibility.

It is evident that design parameters for the arc heater depend on the specifications for wind tunnel performance. The pertinent arc heater parameters are power to the air, arc chamber pressure, air enthalpy, air purity and air flow uniformity. True simulation of full scale re-entry flight conditions would, of course, be greatly desired. However, a compromise specification must be accepted since pressures in thousands of atmospheres and power in hundreds of megawatts cannot yet be envisioned for continuously operating, low contamination air heaters.

This investigation continued the work described in WADD Technical Report 60-354, "Study of Arc Heaters for a Hypersonic Wind Tunnel". The objectives for the work described in this report were selected to combine the attainment of further basic information on arc-heated gas fluid mechanics and knowledge of arc air heater engineering principles with the development of a practical device suitable for powering a four megawatt hypersonic wind tunnel for aerodynamic research. The approach taken involved further study of the arc air heating concept described in WADD TR 60-354 as the High Voltage arc heater. The promising preliminary results were confirmed, scaling laws established, operation with alternating current instead of direct current investigated briefly and a four megawatt heater designed, constructed and tested at the maximum power of two megawatts.

Hypersonic flight simulation at lower altitudes in wind tunnels with increased test section diameters will require arc air heaters with power capabilities in the multi-megawatt range. Forty and 100 megawatt arc heaters are envisioned for operation at chamber pressures of 200 atmospheres and enthalpies as high as 15,000 Btu

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per pound of air. The capabilities of a possible High Voltage design for these power levels are discussed. With reference to the power rating of arc air heaters, the convention is adopted of using a nominal figure, giving the actual power delivered to the heater at a specific operating point well within its capabilities.

II. DEVELOPMENT OF HIGH VOLTAGE ARC AIR HEATERS

As shown in Figure 1, the basic elements of the High Voltage heater are two coaxial tubular electrodes separated by an inlet chamber. One electrode has an opening for exhausting heated air. The early work showed that an arc air heater of this design operated at unusually high voltages, in excess of 2000 volts, and was relatively efficient. The water-cooled copper electrodes were found to have very low erosion rates. Swirl flow of inlet air was usually necessary for proper heater performance and a magnetic field coil around the rear electrode was found to reduce erosion. Constricting the opening of the nozzle electrode increased chamber pressure to permit high test section Mach numbers in eventual wind tunnel use.

Scaling Studies

Scaling studies were performed with High Voltage arc air heaters to learn whether or not a simple scaling law could be established to predict operating characteristics of multi-megawatt devices. A suitable relationship was found, based on a scaling factor N, defined as the ratio of the linear dimensions in the scale model to those of a High Voltage arc heater nominally rated at two megawatts power input, the Model 120.

It was found that effluent air enthalpy and arc chamber pressure of an N scale device are equal to those of the basic N=1 arc heater providing the arc current in the scale model is N times that in the basic arc heater and the air flow rates per unit area are the same. Under these conditions, the scale model arc voltage and power will equal those of the basic arc heater multiplied by N and N^2, respectively. The law can be restated in simple formulas using the subscript m to indicate the model and b to represent the N=1, Model 120 arc air heater.

Let N = $(\text{Linear dimensions})_m/(\text{Linear dimensions})_b$
I = Arc current in amperes
V = Arc voltage
K = Arc power
$\dot{W}$ = Air flow rate in Lb/sec
A = Flow area of nozzle electrode in sq. in.
H = Air enthalpy in Btu/lb
P = Arc chamber pressure in psia

Establish: $I_m = NI_b$
$(\dot{W}/A)_m = (\dot{W}/A)_b$

Result: $H_m = H_b$
$P_m = P_b$
$V_m = NV_b$
$K_m = N^2K_b$.

These simple scaling laws do not fit the experimental data exactly. Heater voltage increases slightly less rapidly than with the first power of N at constant weight flow rate per unit area and normalized current. In addition, arc heater efficiency tends to increase slightly with N. Hence the air enthalpy at constant $\dot{W}/A$ and I/N is almost independent of N, except that at very low air flow rates the enthalpy seems to be higher in small heaters.

The scaling law was derived chiefly from experimental data secured with three models of the High Voltage arc air heater. The Model 120, N=1, device was designed for high pressure operation, pressure-tested to 6000 psi, and operated satisfactorily over a wide range of conditions at arc chamber pressures as high as 1000 psig. Smaller heaters, with inside linear dimensions exactly one-half (N=1/2) and one-fourth (N=1/4) those of the "full-size" heater, were also built and tested. The smoothed experimental data were plotted as a function of nozzle constriction at several values each of normalized air flow rate and arc current for each value of N. Crossplotting gave the operating parameters as a function of scaling factor at constant values of normalized nozzle constriction, air flow rate and current. These plots were used to extrapolate to the values of N required for higher power capabilities. Another set of crossplots using normalized current as the independent variable at constant nozzle constriction, normalized unit air flow rate and scaling factor permitted extrapolation to the arc currents necessary for achieving high air enthalpies. Complete operating characteristics could then be derived at any desired value of N, $\dot{W}/A$, and I.

The basic experimental data are presented on Figures 2 to 7 in the form of air enthalpy and heater efficiency plotted versus air flow rate at the conditions selected for scaling tests. Each heater was tested over a range of air flow rates, with both unconstricted and constricted discharge nozzles at three normalized arc currents, I/N = 200, 400 and 800 amperes. Data for unconstricted heaters are plotted in Figures 2 to 4. Similar data were also taken with a 1/2 inch constriction at the exit of the full size heater, and with constrictions of 1/4 inch and 1/8 inch on the scaled heaters. These data are plotted in Figures 5 to 7. For both constricted and unconstricted operation, higher arc currents give higher air enthalpy and lower efficiency. Increasing air flow rate decreases enthalpy and raises efficiency. At constant current, both enthalpy and efficiency tend to become constant at fairly high air flow rates.

The area of the swirl air inlet holes of the N=1/4 High Voltage heater was varied to study the effect of inlet air Mach number on performance. This effect was found to be quite noticeable, as shown by the data in Table 1 below. When the data for a particular gas flow rate are replotted against inlet pressure ratio, as shown in Figure 8, the improvement in heater performance as pressure ratio increases is seen to be very rapid at low inlet Mach numbers, increasing very slowly as choked inlet flow is reached.

Table 1

Effect of Inlet Air Mach Number on Arc Voltage

Quarter-size heater, unconstricted, 50 amperes arc current

Air Flow Rate Lb/sec	Inlet Air Mach No. → 1	0.50	0.25	Very low
	Arc Voltage			
0.003	300	285	-	280
0.009	490	470	440	400
0.011	560	540	510	440

An appreciable radial pressure gradient exists in the High Voltage arc heater swirl chamber; pressure increases with distance from the axis. The radial pressure gradient may be associated with the interaction between (1) the tendency of the tangential velocity in the swirl chamber to increase as the axis of the torch is approached due to conservation of angular momentum and (2) the viscous and shock wave dissipative mechanisms which become very strong as velocity approaches that corresponding to Mach 1. Pressures measured at the wall of the swirl chamber were appreciably higher than the rear electrode pressure. The pressures measured on the axis of the rear electrode agreed with pressures calculated from measured air flow rate, enthalpy and constriction.

Model 120 High Voltage Arc Air Heater

A fairly extensive investigation of operating characteristics was made, a portion of which was described in the preceding discussion on scaling laws. Operating characteristics for the unconstricted arc air heater and for the heater operating with 1/2-inch diameter constriction are given on Figures 2 to 7. These curves give enthalpy and efficiency (from which voltage and power to the air can be calculated) as a function of air flow rate at arc currents of 200, 400 and 800 amperes. Figure 9 gives more complete data on operation at 400 amperes with a 1/2 inch constricting nozzle.

Tests were also made using the Model 120 arc heater with constricting nozzles having diameters of 3/8, 1/4 and 3/16 inch. The tests with 3/8 and 3/16 inch constrictions were made with short nozzle electrodes to determine the improvement in efficiency which could be obtained. Data with the 3/8 inch constriction at 400 and 800 amperes are plotted in Figures 10 and 11.

An arc chamber pressure of 1000 psig was successfully attained in tests with the 3/16 inch diameter constriction, at an enthalpy of 1900 Btu/lb and an efficiency of 54%. The operating parameters are shown in Figure 12.

It has been found that the minimum nozzle electrode length required for stable operation is less for smaller diameter constrictions. The advantage of using an electrode length appropriate to the test conditions is apparent from the data plotted in Figure 13 of enthalpy and efficiency versus constriction. The increase in efficiency due to the shorter electrode at 3/8 inch diameter constriction, 400 amperes arc current and 0.104 lb/sec air flow rate is seen to be about 11%. The enthalpy was measured to be 3700 Btu/lb, instead of the interpolated value of 2800 Btu/lb expected for the longer electrode.

Model 120 arc air heater operating data are given in Table 2 for various constrictions, arc currents and for two different air flow rates at each arc current. The data presented for the higher air flow rate represent the highest power point at that constriction and current.

Table 2

Model 120 Arc Heater Operating Data

Constr. Dia. Inch	Arc Current Amps	Arc Voltage Volts	Arc Eff. %	Air Flow Rate Lb/sec	Air Enthalpy Btu/lb	Air Power KW	Air Ch. Pres. Psig
none	200	840	62	0.04	2350	104	--
		2840	78	0.21	2100	446	--
	400	840	55	0.062	2800	185	--
		2330	70	0.27	2300	652	--
	800	920	55	0.094	4150	409	--
		1150	59	0.135	3800	546	--
1/2"	200	840	55	0.042	2100	88	35
		1470	61	0.074	2300	178	70
	400	800	55	0.042	3800	180	40
		4080	66	0.375	2750	1078	400
3/8"	400	900	53	0.042	4350	191	80
		1630	55	0.104	3250	355	190
	800	1440	47	0.135	3850	548	280
		1870	52	0.189	3950	790	410
1/4"	100	660	47	0.010	3200	34	28
		880	53	0.021	2200	48	52
	200	760	45	0.021	3200	68	74
		2840	53	0.20	1600	358	650
	400	1305	40	0.079	2500	210	300
		1890	43	0.123	2500	327	510
3/16"	200	780	41	0.021	2900	64	120
		2960	54	0.16	1900	321	1000

The data show that diameter of the nozzle constriction is one of the important design parameters and that it has a determining effect on the operating characteristics of the High Voltage arc air heater. The throat area of the constriction affects operating pressure directly and also indirectly affects arc voltage, air enthalpy and heater electrical efficiency.

The effect of current, I, on operating voltage, V, at fixed gas flow rate and constriction has been found to be given very approximately by the equation $V = k/I^{\frac{1}{4}}$. The well known nature of arc current-voltage characteristics suggests the volt-ampere curve should level off and start rising at higher currents.

The Model 120 High Voltage arc air heater can be operated satisfactorily with direct current connections of either polarity. All of the data recorded in this report were obtained with the nozzle electrode connected to the negative terminal of the power supply unless specified otherwise. Although a change in polarity sometimes increases arc stability, the arc voltage and heater efficiency are lowered. The effect of changing polarity is given in Table 3 for arc air heater operation with a 1/4-inch diameter constricting nozzle. Jet stability is indicated by rms percentage of brightness (the method of measurement is described below).

Table 3

Effect of Polarity on Performance of the Model 120 Arc Heater

Constriction dia. 1/4 inch, air flow rate 0.077 lb/sec, 200 amperes arc current

		KW Power					
Nozzle Electrode Connection	Voltage	Loss to Rear Electrode	Loss to Nozzle Electrode	in Air	Eff. %	Air Enthalpy Btu/lb	Rms Brightness Fluctuation %
Negative	1515	35	115	153	51	1900	25
Positive	1410	72	97	113	40	1400	14

During the course of the investigation, the Model 120 High Voltage arc air heater was operated at a maximum arc chamber pressure of 1000 psig, an enthalpy of more than 5000 Btu/lb and with a maximum power in the air of 1.1 megawatts. These peak values were not obtained simultaneously and were, in some cases, limited by factors other than the arc heater. Complete operating data are given in Table 4 for the various record values, including a "compromise" where an arc chamber pressure of 400 psig was attained with an enthalpy of about 4000 Btu/lb of air at 800 kilowatts of power in the air jet. Contamination in the highest power run was about 700 parts per million by weight, determined by measuring electrode weight losses. The arc air heater was operated for 2 to 10 minutes at each of the peak values without visual deterioration.

Table 4

Record Values for the Model 120 Arc Heater

		Arc			Air			
Record	Constr. Dia. Inch	Voltage Volts	Current Amps	Eff. %	Flow Rate Lb/sec	Enthalpy Btu/lb	Power KW	Chamber Pressure Psig
Power to Air	1/2"	4080	400	66	0.375	2750	1078	400
Pressure	3/16"	2960	200	54	0.156	1900	321	1000
Enthalpy	none	750	600	53	0.044	5250	241	--
Compromise	3/8"	1870	806	52	0.189	3950	790	410

Effluent Characteristics of Atmospheric Pressure Jets

Uniformity in time and space of the effluent from the arc heater is very important in aerodynamic studies. Contamination level, particularly of substances which are either solid or might plate out as solids on models immersed in the testing stream, is also very important. A considerable effort was devoted to the measurement of stability, uniformity and contamination, and the effect of operating parameters on these, particularly stability.

Fluctuations in brightness of the effluent are useful as an indication of fluctuation in enthalpy, since higher temperature gas is in general more luminous. For effluent jet temperatures and diameters used in the present work, the jets are optically thin (self-absorption is negligible) and a detector then averages the emissive contribution of all volume elements in the line of sight. This enables high speed photography to show both time and space variations in enthalpy. Such high speed pictures have shown that fluctuations do exist, and that the major fluctuations affect the whole cross-section of the jet. If, instead, streaks or specks had been seen in the high speed films, this would have indicated severe local irregularities. Since the high speed photographs indicated a pronounced tendency to general lightening and darkening of the image of the atmospheric pressure supersonic jet, a phototube system could be and was used for convenient measurement of magnitude and frequency of fluctuation.

A dual beam oscilloscope was used in the stability work to obtain brightness and voltage traces. Light from the heater effluent was imaged at 3:1 reduction on a 1/4 inch diameter iris in front of a Type 922 phototube. The voltage trace was obtained from a divider resistance across the power connections to the heater. Single traces were photographed at a variety of oscilloscope sweep speeds. Most of the traces showed a sizeable 360 cps component in the arc heater voltage, undoubtedly due to the three phase bridge rectifier characteristics of the power supply. There was little correlation between the light and voltage fluctuations. The brightness trace had noticeable frequency components of 120 cps, connected with phase unbalance in the power supply, and a somewhat random fluctuation with a frequency just under 1000 cps.

The average deflection, and the "average" peak-to-peak fluctuations were read for each trace. The rms fluctuation level was then calculated by dividing the peak-to-peak value by the product of average value and appropriate factor. The factor for a square wave is 2, for a sine wave $2\sqrt{2}$ and for a sawtooth wave $2\sqrt{3}$.

The brightness of the heater effluent increases with a high power of the effluent enthalpy. Measurements at two gas flow rates gave an average exponent of about 6. Data of Kivel and Bailey[1] also lead to an exponent of 6 for the dependence of brightness on enthalpy at atmospheric pressure and enthalpies in the range of 2000 to 8000 Btu/lb. Brightness fluctuations may be related to velocity and temperature fluctuations. For operation with appreciable constriction at the exit of the heater, chamber pressure and effluent Mach number tend to remain almost constant, although fluctuations exist in mass flow, velocity and temperature. For constant Mach number, the velocity of sound and jet velocity are proportional to the square root of enthalpy. Thus, as shown below, the rms velocity fluctuations are estimated as only 1/12 of the brightness fluctuations.

Let ΔB_r = Root mean square effluent brightness fluctuations

ΔB_p = Peak to peak effluent brightness fluctuation

B_a = Average brightness

F = Brightness trace factor

ΔH_r = Root mean square effluent enthalpy fluctuations

H_a = Average enthalpy - Btu/lb

ΔV_r = Root mean square velocity fluctuations

V_a = Average effluent velocity - Ft/sec

$$\Delta B_r = \Delta B_p / F$$

$$B_a = k_1 H_a^{6}$$

$$\frac{\Delta H_r}{H_a} = \frac{1}{6} \cdot \frac{\Delta B_r}{B_a}$$

$$V_a = k_2 H_a^{\frac{1}{2}}$$

$$\frac{\Delta V_r}{V_a} = \frac{1}{12} \cdot \frac{\Delta B_r}{B_a}$$

The table below reports some of the fluctuation measurements made on the effluent of the Model 120 High Voltage arc air heater. In some cases, simultaneous high speed motion pictures were taken to establish spatial uniformity.

[1] B. Kivel, K. Bailey, "Tables of Radiation from High Temperature Air," Avco Research Report 21.

Table 5

Model 120 Arc Heater Effluent Fluctuation Measurements

Constr. Dia. Inch	Arc: Current Amps	Arc: Voltage Volts	Air: Flow Rate Lb/sec	Air: Enthalpy Btu/lb	Air: Rms Brightness Fluctuation %
1/2"	200	845	0.031	3050	10
	200	1530	0.074	2650	11
	300	1800	0.112	2950	13
1/4"	200	1515	0.077	1900	25
	400	1290	0.077	2600	26
	400	1890	0.123	2500	13

Data from runs in which contamination was measured by weighing electrodes before and after the test are given below.

Table 6

Contamination Measured with the Model 120 Arc Heater

Constr. Dia. Inch	Chamber Pressure Psig	Arc: Voltage Volts	Arc: Current Amps	Eff. %	Air: Flow Rate Lb/sec	Air: Enthalpy Btu/lb	Air: Power KW	Air: Contamination Wt. %
*1/4"	520	2280	250	52	0.152	1900	300	0.04
1/2"	400	4080	400	66	0.375	2750	1078	0.07
1/4"	510	1890	400	43	0.123	2500	327	0.12

*Run lasted 21 minutes without noticeable change.

Effluent Characteristics in a Wind Tunnel

A few tests were made with the half-size High Voltage heater connected to the Speedway continuous, cooled-wall hypersonic tunnel. The heater was used to feed hot air to a 3/16 inch throat diameter nozzle, giving a 1 inch diameter free jet with a Mach number of about 5 in the test section. A schematic diagram of the tunnel is shown on Figure 14, and a photograph of an arc heater connected to the tunnel on Figure 15.

Air to the wind tunnel system flows through the heater, the expansion section, the test section and the flow section of the wind tunnel, then through a heat exchanger, filter, vacuum valve and vacuum pump (a Beach-Russ Model RP750 with a displacement of 845 cfm). The heat exchanger was designed by the Speedway Engineering Laboratory to cool 0.02 lb/sec of air from 6000°R to below 200°F, with an inlet pressure in the range from 10 to 50 mm Hg absolute. The exchanger employs 43 1 inch I.D. stainless steel tubes, 7 feet long, with cross-baffled water on the 10 inch I.P.S. shell side. The filter protects the vacuum pump by stopping any solid material produced by erosion in the arc heater or test section. The vacuum valve is used to adjust test section ambient pressure.

A number of still and motion picture records were made of the jet in the wind tunnel. Shock waves from a stagnation pressure probe introduced into the stream could readily be photographed, as seen in Figure 16. The probe consists of a 0.055 inch I.D. stainless steel tube, surrounded by two larger tubes for water-cooling, resulting in an outside diameter of 0.203 inches.

The stagnation pressure profile shown in Figure 16 was obtained at the conditions listed in Table 7, using a geared traverse, and a vacuum valve setting selected to give parallel flow in the free jet. Based on the stagnation pressure ratio of 290 to 8.6 mm Hg, the Mach number is calculated to be 5.1, and is uniform to $\pm$ 0.2 across the core of the jet. Locating the pressure probe at the edge of the jet produced a visible Mach wave in the stream. This Mach wave was measured on a photograph as being at an angle from the stream axis of $12.5^{\circ} \pm 1^{\circ}$, for a calculated Mach number of 4.6 $\pm$ 0.3. Mach number can also be calculated from the measured chamber and free stream pressures if isentropic expansion is assumed. For air at 2930 Btu/lb and 85 psig stagnation conditions, the Mach number after expansion to 8.6 mm Hg is 4.3. The mean of these different measures is a Mach number of 4.7.

Table 7

Wind Tunnel Measurements

Air Flow Rate	0.0125	Lb/sec
Arc Current	170	Amperes
Arc Voltage	460	Volts
Power to Heater	78.1	KW
Power to Air	36.9	KW
Efficiency	47	%
Air Enthalpy Added	2800	Btu/lb
Air Enthalpy	2930	Btu/lb
Chamber Pressure	85	Psig
Throat Dia.	3/16	Inch
Free Jet Dia.	1	Inch
Test Section Pressure	8.6	mm Hg
Test Section Velocity	10,500	Ft/sec
Expansion Pressure Ratio	600	
Calculated Isentropic Mach Number	4.3	
Pitot Pressure Ratio	33.8	
Calculated "Pitot" Mach Number	5.1	
Angle of Mach Wave	12.5	Degrees
Mach Number from Mach Angle	4.6	

III. MODEL 124 HIGH VOLTAGE ARC AIR HEATER

The mechanical specification set up for the High Voltage heater for the WADD wind tunnel was a design suitable for operation with four megawatts delivered to the heater at chamber pressures of 1500 psi. The minimum performance specification was operation at 500 psi arc chamber pressure, 2000 Btu/lb air enthalpy, two megawatts of power delivered to the heater, more than 50% efficiency and a running time longer than one minute.

Design

The general design is similar to that given on the schematic diagram of Figure 1. A photograph of the heater prior to testing is included as Figure 17. Arc heater power and pressure specifications determined the electrode tubing sizes and wall thicknesses. The 1500 psi operating pressure requirement is a stringent one, since mechanical strength of the electrode becomes the limiting factor. A safety factor of four was used in computing stress in electrodes to take account of the reduction in strength during operation at high temperatures. Since the yield point of soft copper is 10,000 psi, arc heater operation at high internal pressures requires the use of either higher strength alloy copper tubing in the electrodes or high pressure cooling water to reduce the pressure differential that the electrodes have to withstand.

The cooling water jackets in the Model 124 arc air heater were designed to withstand 6000 psi before reaching yield stress, which should permit cooling water pressures as high as 3000 psi to be used. However, water pressure above 2000 psi should be used very cautiously, since differential pressures can be encountered that may lead to electrode buckling. An alternate solution for high pressure operation is the use of special high strength, high thermal conductivity copper alloys. One such alloy has a room temperature yield strength 4.5 times that of soft copper. A set of soft copper electrodes and an interchangeable set of higher strength alloy electrodes were fabricated for the Model 124 heater. The heater is suitable for use at 750 psi internal arc chamber pressure when the soft copper electrodes are used with 300 psi cooling water. Substitution of the alloy electrodes permits a maximum operating pressure of 1500 psi with 300 psi cooling water.

A limiting factor in High Voltage arc air heater operation is the amount of heat loss to electrodes that can be dissipated without an unacceptable increase in electrode erosion rates. In the Model 124 arc heater, the cooling water flow rate with 300 psi water pressure drop across the heater is 260 gpm, enough water to dissipate almost three megawatts.

The heater was designed to produce air enthalpies in the range of 2000 to 8000 Btu/lb when operated at arc currents of 400 to 2000 amperes. Corresponding arc voltages at a four megawatt power level are 10,000 and 2000 volts respectively.

Most efficient heater operation is obtained with near sonic inlet air injection velocities. Thus operation at 500 psi internal pressure requires air supplied at 1000 psi and operation at 1500 psi would require 3000 psi air supply pressure. For a given power to the air, the mass flow rate is inversely proportional to enthalpy. The highest mass flow will therefore occur at the lowest enthalpy of interest, approximately 2000 Btu/lb. These considerations establish the air flow rate of the Model 124 arc air heater at 0.5 lb/sec for each megawatt delivered to the air.

Performance

Due to power supply and time limitations, the Model 124 High Voltage arc air heater was given only sufficient performance testing to establish its ability to satisfy minimum operating specifications. Performance curves are presented for operation at 400 ampere arc current and constrictions of 3/8", 7/16" and 0.525" throat diameter plus 800 ampere data with the 0.525" constriction. Using correlations developed in the scaling studies, predicted charts are worked out for currents of 800 amperes at 3/8" and 1" constriction, and for 1600 amperes at 1" constriction.

In the course of the test work, two additional variables were briefly studied: nozzle electrode length, and orientation of the gas inlet holes. Early test work with the Model 124A showed that the nozzle electrode length was insufficient to cause the arc to terminate upstream of the throat of the constriction. As a consequence, some erosion of the throat occurred, the effluent cross-section was observed to be inhomogeneous, with a hot core, and the chamber pressure was lower than expected for the corresponding air enthalpy, air flow rate, and constriction diameter. Lengthening the nozzle electrode (this modification was called the Model 124B) was found to eliminate the throat erosion and sharply reduce the difference between measured and calculated pressures. Changing the orientation of the swirl inlet ports so that the tangential component of the inlet velocity was reduced was found to have a similar effect by reducing arc length and arc voltage. Unless otherwise specified, the data in the tables were obtained with the "B" modification of the Model 124, using a tangential component about 2/3 of the inlet velocity.

Figures 18, 19 and 20 give performance data at 400 ampere arc current for constriction diameters of 3/8 inch, 7/16 inch and 0.525 inch. For a fixed air flow rate and current, as constriction diameter increases enthalpy and efficiency increase, and pressure decreases.

Increasing current to 800 amperes raises enthalpy at a given gas flow rate, as seen in the performance data for 0.525" constriction plotted in Figure 21. At a specified arc current and constriction diameter, there exists a minimum air flow rate, determined by rapid electrode erosion. Similarly, a minimum nozzle electrode length exists for a given air flow rate. This minimum length is shorter at high currents, which permits obtaining higher enthalpies than can be reached if geometry is assumed to be fixed. Figure 22 shows the gain in enthalpy achieved by reducing nozzle electrode length (Model 124A instead of 124B).

Data were obtained on fluctuation level in effluent brightness and in heater voltage at most of the operating conditions. Fluctuation levels in rms effluent brightness ranged from 14% to 20%, with smoother effluents at higher air flow rates. The correlation between this brightness fluctuation and temperature discussed in the preceding section implies that the rms velocity fluctuation will be of the order of 1 to 2%. The rms fluctuation level in voltage was less than that in brightness, about 6% to 10%.

Record conditions reached in the tests of the Model 124 at Speedway are listed in Table 8. The pressure and power to the air limits were set by the power supply, but peak enthalpy is near the limit due to erosion of the rear electrode.

Table 8

Record Values for the Model 124 Arc Heater

Data for Model 124B, using Speedway 2 megawatt power source

		Arc			Air			
Record	Constr. Dia. Inch	Current Amps	Voltage Volts	Eff. %	Flow Rate Lb/sec	Enthalpy Btu/lb	Power KW	Chamber Pressure Psig
Power to Air	.438	400	4450	59	.43	2300	1050	505
Pressure	.375	400	4250	50	.36	2200	850	575
Enthalpy*	.525	800	1200	54	.08	5900	500	80
Efficiency	.460	250	2900	64	.17	2600	465	180

*Short nozzle electrode (Model 124A)

Performance calculations were made for a heater discharge constriction of 1 inch at three currents, and for 3/8" at one additional current, to provide more complete information on the properties of the Model 124. The calculations used the results of the scaling studies as a guide. Results appear on Figures 23 to 26. Consideration of both experimental and computed data leads to the summary of the Model 124 arc heater operation given below.

Table 9

Model 124 Arc Heater Operating Data

Constr. Dia. Inch	Arc: Current Amps	Arc: Voltage Volts	Arc: Eff. %	Air: Flow Rate Lb/sec	Air: Enthalpy Btu/lb	Air: Power MW	Air: Chamber Pressure Psig
1	400	1300	70	0.1	3700	0.4	10
		8700	78	1.0	2600	2.7	230
	800	1060	58	0.1	4400	0.5	15
		7500	69	1.0	3900	4.1	270
	1600	1430	49	0.2	5300	1.1	50
		3840	53	0.6	5100	3.2	170
.525	400	1610	58	0.1	3400	0.4	80
		9900	73	1.0	2700	2.9	830
	800	1300	44	0.1	4200	0.4	90
		8200	56	1.0	3500	3.7	1000
7/16	400	1500	49	0.1	3000	0.3	130
		9600	65	1.0	2300	2.5	1170
3/8	400	1800	39	0.1	2700	0.3	160
		10200	53	1.0	2100	2.2	1580
	800	1500	33	0.1	3600	0.4	180
		5200	41	0.6	2700	1.7	1050

Since the optimum performance values listed in Table 8 were limited by the power supply rather than the arc air heater, a second table has been prepared using calculated data for the various constrictions, and assuming adequate power is available. The results appear in Table 10.

Table 10

Predicted Optimum Performance of the Model 124 Arc Heater

Record	Constr. Dia. Inch	Arc: Current Amps	Arc: Voltage Volts	Arc: Eff. %	Air: Flow Rate Lb/sec	Air: Enthalpy Btu/lb	Air: Power MW	Air: Chamber Pressure Psig
Power to Air	1	800	7500	69	1.0	3900	4.1	270
Pressure	3/8	400	10000	53	1.0	2100	2.1	1600
Enthalpy	.525	800	1200	54	.08	5900	0.5	80
Efficiency	1	400	8700	78	1.0	2600	2.7	230
Compromise	.525	800	8200	56	1.0	3500	3.7	1000

Services

Services necessary for operating the Model 124 arc heater are compressed air, direct current power and cooling water. The air supply must be capable of furnishing a sustained flow rate of over 1 pound per second at a pressure of 2000 psi for heater operation at 1000 psi arc chamber pressure.

The negative slope of the volt-ampere arc characteristic curve requires a power supply having a drooping volt-ampere characteristic. Open circuit voltage should be double the operating voltage and short circuit current should not exceed operating current by a factor of more than two. The power supply should supply at least four megawatts of direct current at operating currents in the range from 400 to 2000 amperes. Corresponding operating voltages will be 10000 to 2000 volts.

Cooling water is required at a minimum pressure of 300 psi. If electrode pressure compensation is necessary for operation at high arc chamber pressure, the cooling water pressure must be increased. The desired flow rate of cooling water for the Model 124 arc heater is 260 gallons per minute. Electrically conductive cooling water is undesirable.

IV. PARALLEL OPERATION OF ARC AIR HEATERS

Feeding the effluent of more than one heater into a common plenum and constricting nozzle is a straightforward way to increase power to the air and to smooth effluent fluctuations. Design of the plenum depends on the relative importance of heat loss and smoothing since improved smoothing generally increases heat loss to the plenum walls.

A dual heater nozzle was designed to permit connection of two unconstricted Model 120 arc air heaters to a plenum and exit nozzle. In the tests with the dual heater nozzle, air was supplied separately to the two heaters, and the air inlets were located to give opposite directions of swirl in the hope of achieving swirl cancellation in the effluent jet. Figure 27 is a photograph of the heater with leads disconnected. The angle of intersection of the axes of the two heaters with the plenum walls was chosen to achieve low heat loss by changing the direction of air flow as little as possible. The plenum formed a common ground connection for the two arc heater nozzle electrodes, while separate power sources were connected to the two rear electrodes.

Tests were made with two degrees of constriction, using plenum chamber nozzles with throat diameters of 1/4-inch and of 1/2-inch. The fraction of heat in the gas entering the plenum which was lost in water-cooling the walls of the plenum and exit nozzle depended on the throat diameter of the nozzle and the air flow rate, but only slightly on the gas enthalpy. Figure 28 shows the percentage heat loss versus plenum chamber pressure for both nozzles. It is seen that at 500 psia chamber pressure the expected heat loss for a 1/2-inch nozzle is 10%. The corresponding enthalpy range is 1500 to 3000 Btu/lb of air.

The operation of each heater at balanced conditions appeared to be similar to performance of a single heater with a constriction of half the dual heater throat area. The assembly also operated satisfactorily at unbalanced conditions. A deliberate unbalance in enthalpy from the two heaters was established to aid in determining the degree of mixing of the two jets. Both visual observation and photographs from a position normal to the plane of the two heaters showed a difference in brightness on the two sides of the effluent jet, indicating mixing of the counter-rotating streams was incomplete. Therefore, it appears that swirl cancellation was not achieved in the dual heater tests. This was due at least in part to the design emphasis on minimum heat loss, which tends to be associated with poor mixing.

Measurements of brightness fluctuations averaged over the width of the jet showed a 20 to 50% decrease in fractional fluctuation, with a good deal of scatter in the data. The expected reduction, for two streams of the same intensity and fluctuation level and random phase relation is a factor of $\sqrt{2}$. If fluctuations from the power supply are significant, less reduction in fluctuation level would be expected. The brightness trace has a noticeable but not predominant amount of fluctuation at multiples of 60 cps such as 60, 120, 180 and 360.

The dual heater test data, in conjunction with other test data obtained with the Model 120 arc heater, imply that satisfactory operation can be achieved with as much as two megawatts in the air at more than 500 psia with an overall efficiency above 50%.

V. ALTERNATING VS DIRECT CURRENT POWER

Use of alternating current instead of direct current power for operating arc air heaters for large hypersonic wind tunnels in the multi-megawatt power range is desirable chiefly for economic reasons. It is assumed the installation is to be capable of continuous operation for relatively long periods at frequent intervals, and that energy storage devices are impractical. Under these conditions, the initial expenditure for an alternating current power supply will be less than half as great as that required for direct current and the power supply maintenance cost may be much lower. The elimination of rectifying elements alone will reduce purchase cost by amounts varying from $10,000 to $25,000 per megawatt depending on the desired flexibility and the rectifier cell safety factor. In a 50 megawatt installation, for example, this saving ranges from $500,000 to $1,250,000. Further capital savings will be made where existing sources of high voltage alternating current power can be used with a reactor or resistor to provide arc stability.

The major disadvantage of alternating current arc heater operation is expected to be irregularities in effluent resulting from the periodic power pulses. It is obvious that multi-phase alternating current would be preferable to single phase because of greater effluent stability, more reliable arc operation and lower equipment cost. Further improvements in effluent stability could be achieved by using suitable plenum chambers and frequencies higher than 60 cps.

Because of the advantage of using alternating current power, a small amount of exploratory work was performed to evaluate the performance of three existing types of arc heaters, previously designed for direct current, with alternating current power. The results would guide any future, more extensive investigation. The arc heaters were an early High Voltage heater, Model 118, a model 112 Direct arc heater employing a thoriated tungsten, rod-shaped upstream electrode and a copper nozzle downstream electrode, and a Model 119 Toroidal arc heater in which two concentric, cylindrical copper electrodes are used with the arc rotating in the gas space between them. Schematic diagrams are given on Figures 29 and 30. Photographs of the heaters appear on Figures 31 to 33. Because of limited time, attempts were not made to obtain improved performance with alternating current power by modifying arc heater design.

High Voltage Arc Air Heater

The High Voltage arc heater operated surprisingly well with pure air on single phase, 60 cycle per second, alternating current power. Continuous performance was achieved at power levels of 250 kilowatts to the air. Heater efficiency was essentially not affected by changing from direct to alternating current but arc voltage, power and air enthalpy were reduced. Comparable data are given below in Table 11 and are plotted on Figures 34 and 35 as a function of air flow rate. The data were obtained with a one megawatt High Voltage arc air heater operating at 400 amperes arc current with a 1/4-inch constricting nozzle. Arc tracks on the electrodes show the area used for arc termination is greater with alternating than with direct current. This behavior suggests the maximum value of rms alternating current permitted by electrode cooling ability will be greater than the limiting value with direct current. There is a possibility, therefore, that higher power, and enthalpy approaching or exceeding those attained with direct current will be achieved at equivalent air flow rates by using higher current with alternating current power to compensate for the lower arc voltage.

Table 11

Model 118 High Voltage Arc Heater Performance with Alternating and Direct Current Power

Air Flow Rate Lb/sec	Arc Voltage DC (Volts)	Arc Voltage AC (Volts)	Heater Efficiency DC (%)	Heater Efficiency AC (%)	Air Enthalpy DC (Btu/lb)	Air Enthalpy AC (Btu/lb)	Power to Air DC (Kilowatts)	Power to Air AC (Kilowatts)	Chamber Pressure DC (Psig)	Chamber Pressure AC (Psig)
0.02	600	450	38	27	4300	2100	90	45	70	55
.04	1030	800	42	35	4100	2400	175	100	165	135
.06	1470	1125	45	44	4200	2800	265	180	260	215

The alternating current arc has two important volt-ampere characteristics, the static and the dynamic. Static characteristic curves were obtained for the Model 118 arc heater operating with three air flow rates through a 1/4-inch diameter constricting nozzle. Data on Figure 36 show the rms alternating current arc characteristic has about the same slope as the direct current characteristic, but arc voltages are lower. Thus, power supply circuits forming stable direct current arcs should also be suitable for alternating current arcs. Dynamic arc characteristics showing the hysteresis-like loop relationship between instantaneous values of current and voltage were not measured directly, but dual beam oscilloscope traces of current and voltage were taken. A typical set of traces are given on Figure 37. The traces show current is sinusoidal, voltage approaches a square wave, phase angle is zero and little or no rectification is occurring. Several repetitive traces appear on the photographs indicating the stability of operation. At lower power levels, in the order of 100 kilowatts, some rectification takes place, with an appreciable direct current component appearing.

Although the effluent gas stream appeared visually to be similar to that produced by the arc heater operating on direct current, high speed motion pictures showed periodic brightness fluctuations at a frequency of 120 cps, as expected. These fluctuations could be reduced by multi-phase operation, use of a plenum chamber and by using frequencies higher than 60 cps. Gas contamination appeared negligible based on visual observation of effluent color and examination of electrodes. Quantitative measurements were not made.

Hypothesis for Alternating Current Arc Heater Operating Mechanism

The fact that High Voltage heater operation is independent of the polarity of a particular electrode is a necessary condition for the heater to operate on alternating current but is by no means a sufficient one. It is also necessary that the arc restrike whenever the current passes through zero. The open circuit voltage that has been employed is usually not high enough to cause sufficiently high fields within the arc chamber to break down air, although spontaneous starts have been observed by lowering the chamber pressure.

Insufficient data have been taken to support or disprove any theory regarding the restrike mechanism but the following hypothesis is offered. The difficult time interval is the one when the current goes through zero. The ability of ultraviolet light of the proper wavelength to lower the breakdown potential of a gas is the mechanism proposed to explain arc restriking. As arc current goes through zero the numbers of electrons and ions decrease correspondingly to zero because of extremely fast recombination at this pressure. Thus, the source for the continual replenishment of electrons and ions has disappeared. However, as the electrons and ions recombine, large amounts of very short wavelength electromagnetic radiation are emitted through the resonance lines of first electron-ion recombination and then atom-atom recombination. Although the gas is transparent to radiation of higher wavelengths, the resonance radiation is effectively trapped within the gas because of the high probability for absorption; the photons escape only through a "diffusion" process which is necessarily very long. Thus a relatively slowly decaying source of energetic photons exists. Although this radiation is not capable of ionizing the atoms directly it can ionize the molecules to produce ions and electrons. In addition to the existence of electrons and ions within the gas volume, the electrode must be capable of emitting electrons. The emission mechanism in the High Voltage heater is probably not dominated by thermionic emission. If it were, the arc would, contrary to actual behavior, always restrike to the hottest part.

The hypothesis advanced is that the emission is initiated by energetic photons diffused from the gas with energy considerably above the work function of the electrode. When the high voltage has been reapplied, the field gradient within the chamber is high because of the presence of electrons and ions and because of local surface imperfections. If the electrodes were planar and the field uniform, the field intensity would be about 1000 - 2000 volts/inch. The emitted electrons, and possibly the electrons existing in the gas volume, are accelerated between collisions to an energy great enough to ionize a nitrogen or oxygen atom. The resultant electrons will in turn be accelerated causing further ionization with a subsequent avalanche breakdown. Some of the electrons will recombine causing more ultraviolet radiation to cause propagation of the discharge.

Direct Arc Air Heater

In contrast to the results of trials with the High Voltage heater, the investigation of Direct arc heaters using alternating current yielded poor results for operation at relatively low chamber pressure with unconstricted nozzles. Impractically high ratios of argon to air were necessary to maintain the arc. In addition, operating voltages and power to the gas were unacceptably low. Although arc stability was increased somewhat by raising the ratio of power supply open circuit to operating voltage, satisfactory performance could not be achieved with ratios as high as 25. The direct arc heater operates on direct current with a ratio of two. These comments apply to both classes of direct arc heaters shown on Figure 30, using argon-shielded tungsten cathodes with water-cooled copper nozzle anodes. It was also observed that a large direct current component was present at a level of about one-half that of the alternating current value; and consequently, straight and reverse polarity half-cycles were of unequal duration. This behavior is apparent from the oscilloscope trace in Figure 38.

The effect of open circuit voltage on arc extinction voltage was demonstrated clearly with the Model 112, Type B Direct arc heater using pure argon gas with a 1/2-inch diameter cylindrical nozzle. Raising the power supply open circuit voltage from 900 to 1350 volts increased the extinction voltage from 85 to 120 at constant arc current. The corresponding argon flow rates were 0.053 and 0.078 pounds per second, respectively. The addition of small amounts of air to argon also raised the arc voltage. For example, a 5% addition of air to pure argon increased the arc voltage approximately 60%.

Selected comparative operating data with alternating and direct current power in the Model 112 Direct arc air heater are given in Table 12. The measurements were made with a 1/2-inch diameter cylindrical nozzle in the arc heater. The Type A arc air heater was tested briefly without success.

Table 12

Model 112 Direct Arc Heater Performance
with Direct and Alternating Current Power

Gas Flow Rate						
Argon Lb/sec	Air Lb/sec	Arc Volts	Power to Gas KW	Eff. %	Effective Enthalpy Btu/lb	Remarks
Direct Current Operation						
0.027	0.208	640	240	83	1050	Highest Power
0.005	0.041	250	45	86	1000	Highest Air Concn.
0.027	0.208	680	110	82	500	Highest Voltage
Alternating Current Operation						
0.040	0	100	20	59	-	Highest Power
0.011	0.0005	75	6	50	-	Highest Air Concn.
0.074	0	120	-	-	-	Highest Voltage

Toroidal Arc Air Heater

A Model 119 Toroidal arc air heater was found in earlier trials with direct current power to be capable of attaining relatively high enthalpies with pure air because the combination of large area, well-cooled electrodes with rapid arc motion permitted relatively high arc currents with low air flow rates. For this reason and also because the toroidal arc heater operated well with direct current regardless of electrode polarity, trials were made with alternating current power. The exploratory trials with alternating current showed sustained arc operation could not be achieved for periods longer than about half a minute. The arc position in the heater was sensitive to changes in magnetic field and air flow rates. The sensitivity was such that a satisfactory balance of magnetic and gas dynamic forces could not be reached for continuous alternating current operation using the tested configuration.

Although lack of suitable periods of steady operation prevented reliable thermal measurements with the Toroidal arc heater operating on alternating current, a number of current, voltage and total power data were taken. These data are quite similar to those previously measured during operation with direct current power. Comparative alternating and direct current measurements appear in Table 13 for operation with pure air. Additions of argon to the heater gas were not investigated.

Table 13

Model 119 Toroidal Arc Heater Performance with Alternating and Direct Current Power

			Alternating Current	Direct Current
Air Flow Rate	-	Lb/sec	0.003	0.003
Arc Current	-	Amperes	500	500
Arc Voltage	-		140 rms	140
Arc Power	-	Kilowatts	63	70
Air Enthalpy	-	Btu/lb	-	10,000

VI. ONE HUNDRED MEGAWATT ARC AIR HEATER

A number of aerodynamic and materials projects could utilize a 50 megawatt output source of hot air for either wind tunnel operation or other testing purposes. The study of scaling laws indicates a 100 megawatt arc air heater can be successfully designed to furnish 50 megawatts of power in the air as either a single or a multiple unit. In this section, the performance of 100 megawatt heaters is predicted, using the scaling laws discussed in an earlier part of this report. Some modifications were made in the simple scaling laws in accordance with trends indicated by smaller scale model performance. At this point a word of caution is required since the calculations are based on extrapolation of values obtained from use of the scaling laws far beyond the existence of experimental data. For this reason, it is possible that considerable deviation from predicted performance may be encountered when the arc heaters are actually constructed and tested.

Two models postulated for use in computing service requirements and operating characteristics are a single 100 megawatt heater and three 40 megawatt heaters operating into a plenum chamber. It is assumed that the High Voltage concept is used in the design and that engineering principles developed and discussed for the smaller scale arc heaters will also apply to the 40 and 100 megawatt devices. Examples are the use of (1) sonic velocity air injection, (2) a suitable magnetic field for arc stabilization in the rear electrode, (3) suitable thickness and materials for electrodes to operate safely at the desired pressure, current and temperature and (4) cooling water pressure to balance internal gas pressure in the electrodes.

Three 40-Megawatt High Voltage Arc Air Heaters

To provide information on the multiple heater path to 100 megawatt power, a unit heater specification was set at 20 megawatts in the air at a stagnation pressure of 450 psi with an enthalpy of 3000 Btu/lb and an efficiency of 70%. This specification should insure stable operation at relatively low arc current and low contamination in the air jet. Performance was calculated for operation with nozzle throat diameters of about 1.9 and 1 inch and with free discharge throughout a range of air flow rates from 1 to 5 pounds per second.

Results of the calculations showing predicted performance appear on Figures 39 to 51. The variables plotted as a function of air flow rate are efficiency, enthalpy, power to the air, arc voltage and arc chamber pressure, for a specified arc current. The air flow rate range given on the curves may not coincide exactly with the actual operating range. In general the minimum air flow rate will be established by erratic arc behavior and is a function of arc current. The maximum air flow rate will be set by either the maximum amount of heat that the heater can dissipate or by excessive arc length. Most of these limits can be extended by making suitable modifications in design.

A summary of the data contained in Figures 39 to 47 appears in Table 14 for predicted arc heater operation at an intermediate air flow rate of 3 lb/sec and at arc currents of 2000, 4000 and 6000 amperes.

Table 14

Predicted Performance of 40 Megawatt High Voltage
Arc Heater at 3 Lb/sec Air Flow Rate

	Arc			Air		
Constr. Dia. Inch	Current Amps	Voltage Volts	Efficiency %	Power MW	Enthalpy Btu/lb	Chamber Pressure Psig
none	2000	7900	75	12.0	3800	Low
none	4000	6800	67	18.2	5750	Low
none	6000	6000	62	22.3	7000	Low
1.88	2000	8200	70	11.5	3650	210
1.88	4000	6800	61	16.6	5250	240
1.88	6000	6100	55	20.0	6300	270
0.94	2000	8400	61	10.3	3250	780
0.94	4000	7300	53	15.5	4900	900
0.94	6000	7000	43	18.1	5700	930

The data in Table 14 show the effect on performance of changing arc current and discharge nozzle constriction at constant air flow rate. One important result is the increase in enthalpy and power in the air as arc current rises. Another is the increase in pressure and reduction in power and efficiency as nozzle constriction is increased.

Arc current vs voltage characteristic curves were prepared and are included as Figure 48. The characteristic has a negative slope that increases slightly as the air flow rate is increased. The negative slope characteristic requires a drooping volt-ampere characteristic in the power supply to insure stable arc operation at the desired current.

A summary of optimum performance points of the 40 megawatt arc air heater is given in Table 15. The data show that the design operating conditions are satisfied at an air flow rate of 6 lb/sec with an arc current of 2000 amperes and an arc voltage of 14,000, using a discharge nozzle of 1-7/8 inches diameter. The highest enthalpy of approximately 7500 Btu/lb is achieved at low air flow rate, low power and free discharge. The highest power to the air, 41 megawatts, is also obtained with low pressure and free discharge. The highest pressure is approximately 1500 psi at design power with an air enthalpy of 4400 Btu/lb.

The second, fourth and fifth rows in the table indicate how enthalpy can be gained at the expense of stagnation pressure with constant power in the air (20 megawatts) by proper selection of air flow rate, arc current and nozzle throat area.

Table 15

Predicted Optimum Performance of 40 Megawatt Arc Heater

Record	Constr. Dia. Inch	Arc Current Amps	Arc Voltage Volts	Air Flow Rate Lb/sec	Air Enthalpy Btu/lb	Air Power MW	Air Chamber Pressure Psig
Power to Air	none	6000	10300	6	6500	41	Low
Pressure	0.94	4000	9500	4.2	4400	20	1450
Enthalpy	none	2500	6000	1	7300	7.7	Low
	0.94	6000	7600	3.5	5300	20	1300
	1.88	6000	6200	3	6200	20	280
Design Point	1.88	2000	14000	6	3200	20	440

Two or three 40 megawatt arc air heaters can be used together with a suitable plenum chamber to increase power level. The work reported in section IV indicates that plenum chamber losses are unlikely to exceed 20%. If 50 megawatts are required in the air effluent, an input power of about 62.5 megawatts will be necessary. The additional 12.5 megawatts of power must appear as enthalpy in the effluent from the heaters to satisfy heat losses in the plenum. Suitable arrangements can be made to achieve an output power of 50 megawatts or more as indicated in Table 16. Since the arc heaters would operate in parallel, the operating voltage would be that of a single unit but the total current would be three times that of a single unit.

Table 16

Projected Multiple Operation of Three 40 Megawatt Arc Heaters

Individual Arc Heater: Arc Current Amps	Individual Arc Heater: Arc Voltage Volts	Individual Arc Heater: Air Power MW	Individual Arc Heater: Air Enthalpy Btu/lb	Effluent from Plenum: Air Power MW	Effluent from Plenum: Air Enthalpy Btu/lb	Effluent from Plenum: Air Pressure Psig	Effluent from Plenum: Air Flow Rate Lb/sec
4000	11000	23.5	4400	56	3500	1700	15
6000	7500	25.5	6000	61	4800	380	12
4000	10000	25.0	4700	60	3750	440	15
6000	6500	24.4	6900	59	5600	Low	10

Single 100 Megawatt High Voltage Arc Air Heater

Although the multiple arc heater installation possesses greater versatility, greater flexibility and utilizes power at lower voltage than a single unit, the latter offers advantages of efficiency, simplicity of connections and ease of operation. Calculations similar to those discussed for the 40 megawatt arc heater were made to project operating characteristics of a single 100 megawatt device.

Typical performance relationships are plotted on Figures 49 to 51 for operation with a discharge nozzle throat diameter of 1.3 inch. These data indicate the kind of performance anticipated at various air flow rates. Variables plotted are efficiency, enthalpy, arc voltage and power in the air as a function of air flow rate. A number of conditions selected from these curves and other available calculations appear below. The specific operating points show that design conditions, chosen in this case to be 1800 psi stagnation pressure, 4000 Btu/lb air enthalpy and 50 megawatt power in the air, are obtained with an air flow rate of 11 pounds per second and a nozzle throat diameter of 1.3 inches. The arc current required is 5600 amperes and the voltage is 13,000. Efficiency is about 70%.

The tabulated data also show operating conditions for achieving a maximum enthalpy of 10,000 Btu/lb and maximum pressure of 2600 psi. A study of the table again shows how enthalpy can be gained at the expense of stagnation pressure with constant power in the air (50 megawatts) by proper selection of air flow rate, arc current and nozzle throat area. As in the case of the 40 megawatt arc heaters, the predicted performance may deviate somewhat from actual performance when the arc heaters are built and tested because of the lengthy extrapolation required for the predictions beyond existing experimental data.

Table 17

Predicted Optimum Performance of 100 Megawatt Arc Heater

		Arc		Air			
Record	Constr. Dia. Inch	Current Amps	Voltage Volts	Flow Rate Lb/sec	Enthalpy Btu/lb	Power MW	Chamber Pressure Psig
Power to Air	none	8400	15000	10	7500	80	Low
Pressure	1.3	2800	27000	19	2800	50	2600
Enthalpy	none	8400	4000	2	10000	28	Low
Design Point	1.3	5600	13000	11	4000	50	1800
	2.6	8400	11500	6.5	7500	50	330

Services

These comments apply to operation of either a single 100 megawatt arc heater or three 40 megawatt arc heaters. However, the cooling water requirements of the plenum chamber have not been considered, and would generally be about 20% that of the combined arc heater consumption. The services required for operation are power, cooling water and compressed air. Suitable cooling for maximum power losses consistent with structural integrity will be provided with a water flow rate of about 100 gallons per second at a minimum operating pressure of 300 psi. A higher pressure would be necessary to balance internal pressure when high pressure operation is undertaken. The air system should be able to supply dry gas at a flow rate of 12 pounds per second at sufficient pressure to obtain sonic flow rates in the air injection nozzles for the desired period of continuous performance. For best results the air supply pressure should be approximately double the arc chamber pressure.

The power supply must be capable of furnishing about 100 megawatts of direct current power at operating voltages varying from 6000 to 24000 with corresponding currents of 16000 to 4000 amperes, respectively. If a simple drooping volt-ampere characteristic power supply is to be used, maintenance of desirable arc stability requires the open circuit voltage from the power supply to exceed the operating voltage by a factor of two. In addition, to avoid apparatus destruction, the maximum current available on short circuit should not exceed the operating current by more than a factor of two. At the time construction of a 100 megawatt facility is undertaken, possibilities for reducing the very considerable power supply cost should obviously be carefully evaluated.

VII. SUMMARY AND CONCLUSIONS

1) A simple scaling law was established for the High Voltage arc air heater geometry, stating that constant air stagnation enthalpy and pressure are achieved in the arc heaters if air flow rate per unit area is held constant and arc current is multiplied by a scaling factor. The scaling factor is defined as the ratio of linear dimensions in the heater model under consideration to the similar dimensions in the reference device. Total air flow rate is proportional to the square of the scaling factor. Arc voltage is directly proportional to the scaling factor and power in the air proportional to the square of the scaling factor.

2) A two megawatt High Voltage arc air heater was designed, constructed and operated successfully for 20 minutes without serious electrode erosion. A summary of optimum performance follows.

	Arc			Air			
Record	Current Amps	Voltage Volts	Eff. %	Flow Rate Lb/sec	Enthalpy Btu/lb	Power MW	Pressure Psig
Power to Air	400	4080	66	0.38	2750	1.08	400
Pressure	200	2960	54	0.16	1900	0.32	1000
Enthalpy	600	750	53	0.04	5250	0.24	Low
Compromise	800	1870	52	0.19	3950	0.79	410

3) The effluent jet from High Voltage heaters was examined for stability and uniformity. Rms fluctuations in voltage were 10-15% and rms brightness fluctuations ranged from 6 to 30% in the atmospheric pressure jet. The Mach number was uniform to $\pm$ 4% across the core of the expanded jet at about Mach 5 and 10 mm pressure in a small wind tunnel. Total contamination in the jet was less than 0.1% under recommended operating conditions.

4) Satisfactory operation was attained with two 2-megawatt, Model 120, arc air heaters operating into a plenum chamber. Heat lost to the plenum chamber was less than 12% when the total power in the air was 0.6 megawatt and the plenum chamber pressure was 200 psig. This behavior indicates multiple operation of High Voltage arc air heaters with a plenum is a practical method of attaining high power levels.

5) A four megawatt High Voltage arc air heater was designed, constructed and tested successfully with a 1/2-inch constricting discharge nozzle at maximum power available (2 megawatts). Optimum performance under the test conditions is tabulated below. Projected performance with an adequate power supply and other nozzle constrictions has been calculated and is also given in the table.

Record	Nozzle Constr. Inch	Arc Current Amps	Arc Voltage Volts	Eff. %	Air Flow Rate Lb/sec	Air Enthalpy Btu/lb	Air Power MW	Air Pressure Psig
			Actual Performance with 2 Megawatt Power Supply					
Power to Air	7/16	400	4450	59	0.43	2300	1.05	505
Pressure	3/8	400	4250	50	0.36	2200	0.85	575
Enthalpy	1/2	800	1200	54	0.08	5900	0.50	80
Efficiency	.460	250	2900	64	0.17	2600	.47	180
			Predicted Performance with Adequate Power Supply					
Power to Air	1	800	7500	69	1.0	3900	4.1	270
Pressure	3/8	400	10000	53	1.0	2100	2.1	1600
Enthalpy	1/2	800	1200	54	0.08	5900	0.5	80
Efficiency	1	400	8700	78	1.0	2600	2.7	230
Compromise	1/2	800	8200	56	1.0	3500	3.7	1000

6) Performance of 40 and 100 megawatt High Voltage arc air heaters was projected by use of scaling laws and extrapolation. Optimum values of performance follow. This information should be used with caution because of the sizeable extrapolation of scaling law data involved in the calculation.

Record	Nozzle Constr. Inch	Arc Current Amps	Arc Voltage Volts	Eff. %	Air Flow Rate Lb/sec	Air Enthalpy Btu/lb	Air Power MW	Air Pressure Psig
			Projected Performance - 40 Megawatt Heater					
Power to Air	none	6000	10300	66	6	6500	41	Low
Pressure	1	4000	9500	53	4.2	4500	20	1300
Enthalpy	none	2500	6000	51	1	7300	7.7	Low
Compromise	1	6000	7600	44	3.5	5300	20	1150
			Projected Performance - 100 Megawatt Heater					
Power to Air	none	8400	15000	64	10	7500	80	Low
Pressure	1.3	2800	27000	66	19	2600	50	2400
Enthalpy	none	8400	4000	83	2	10000	28	Low
Compromise	1.3	5600	13000	65	11	4000	48	1750

7) Encouraging results were obtained in preliminary trials of alternating current power with the High Voltage arc air heater. Continuous performance was achieved at power levels of 250 kilowatts in the air at 300 psig stagnation pressure and 3000 Btu/lb enthalpy. Periodic brightness fluctuations occurred at 120 cycles per second.

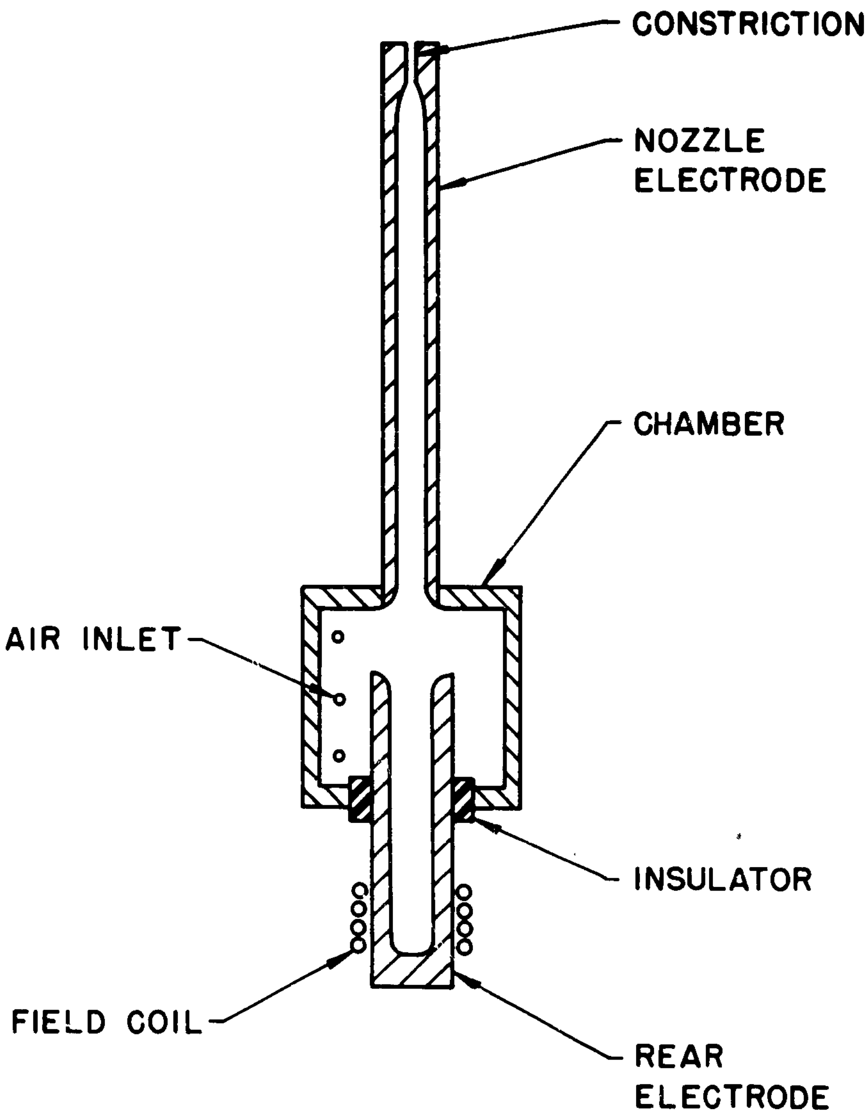


FIGURE 1. HIGH VOLTAGE ARC HEATER SCHEMATIC DIAGRAM

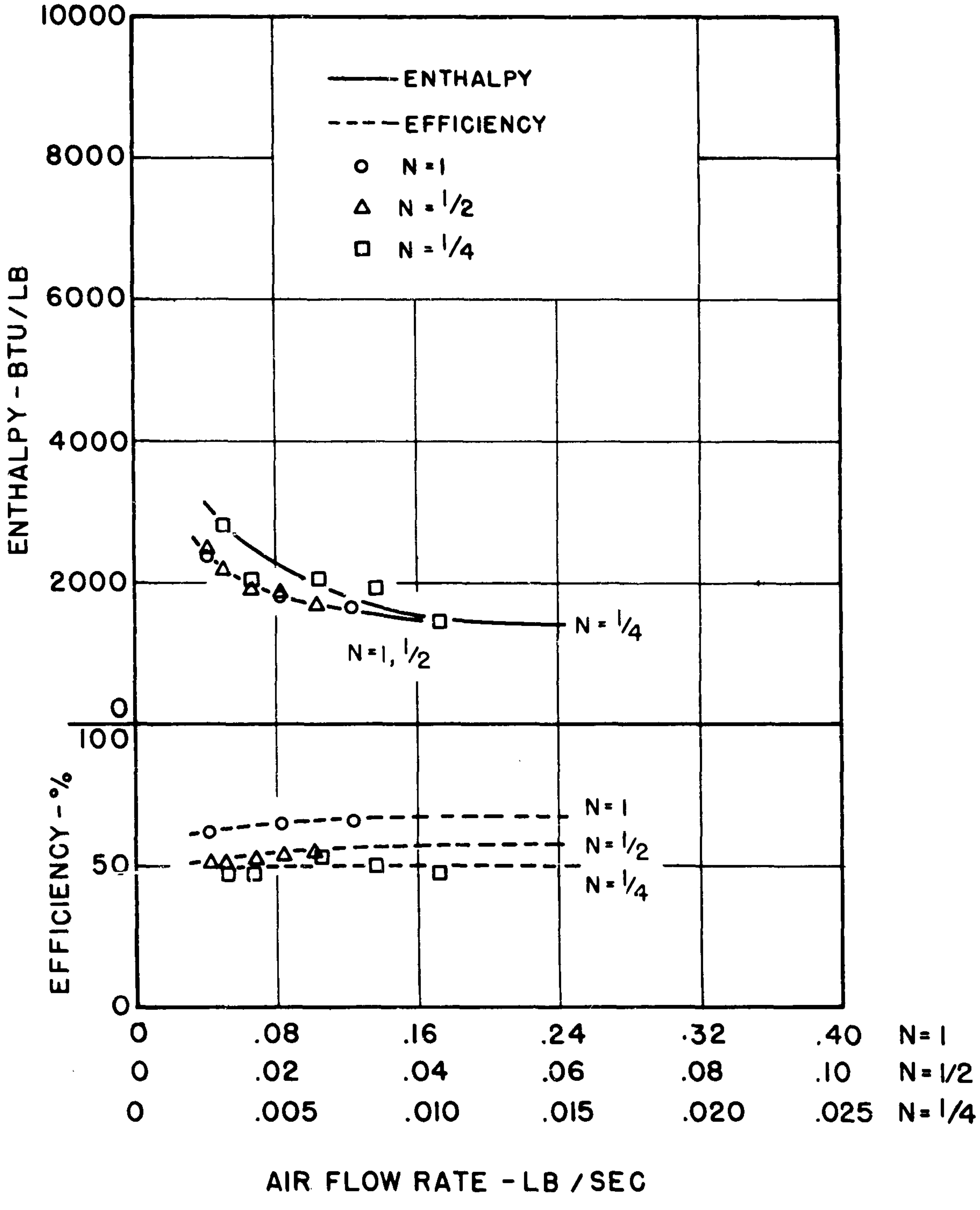


FIGURE 2. SCALING STUDIES (I/N = 200, UNCONSTRICTED)

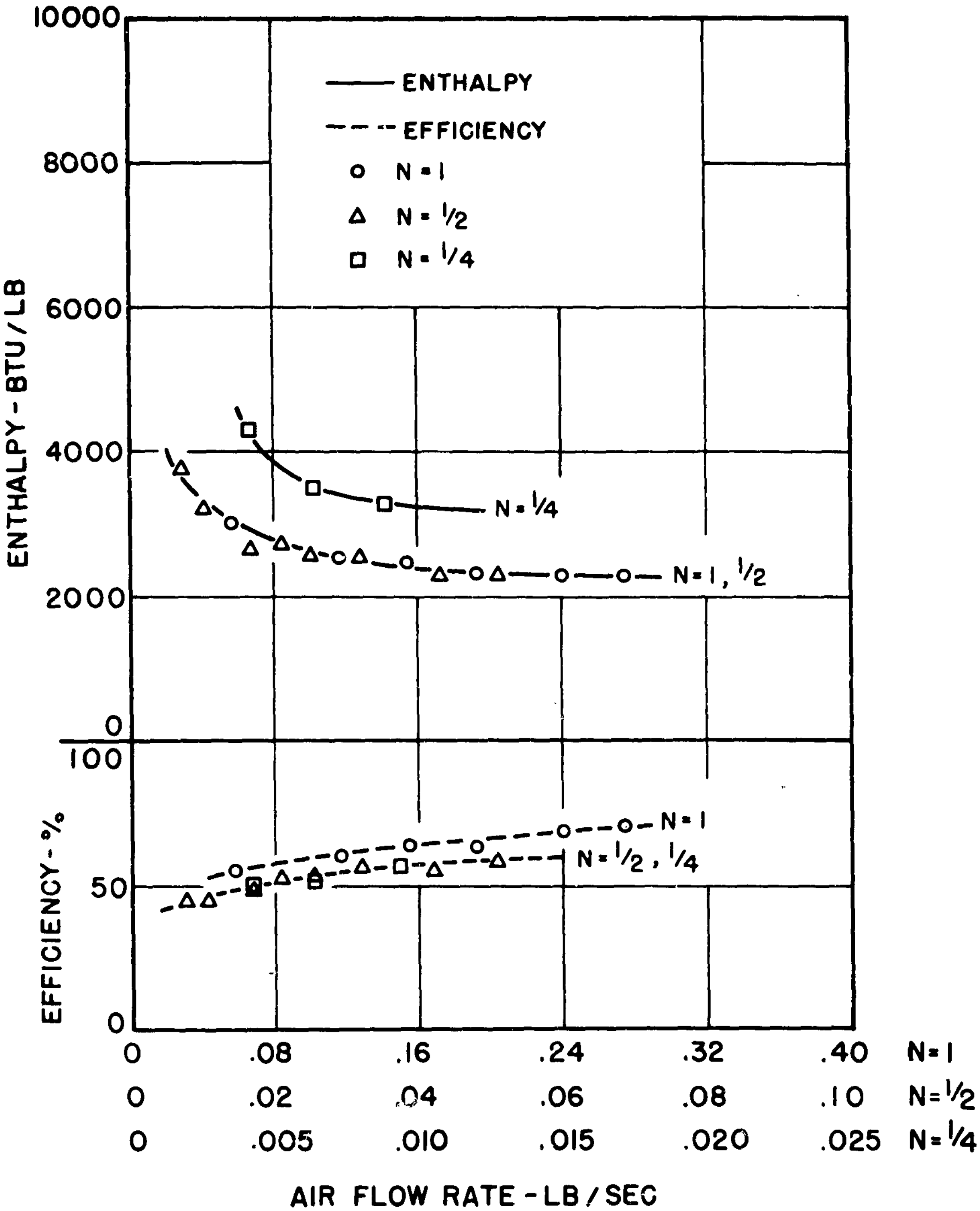


FIGURE 3. SCALING STUDIES (I/N = 400, UNCONSTRICTED)

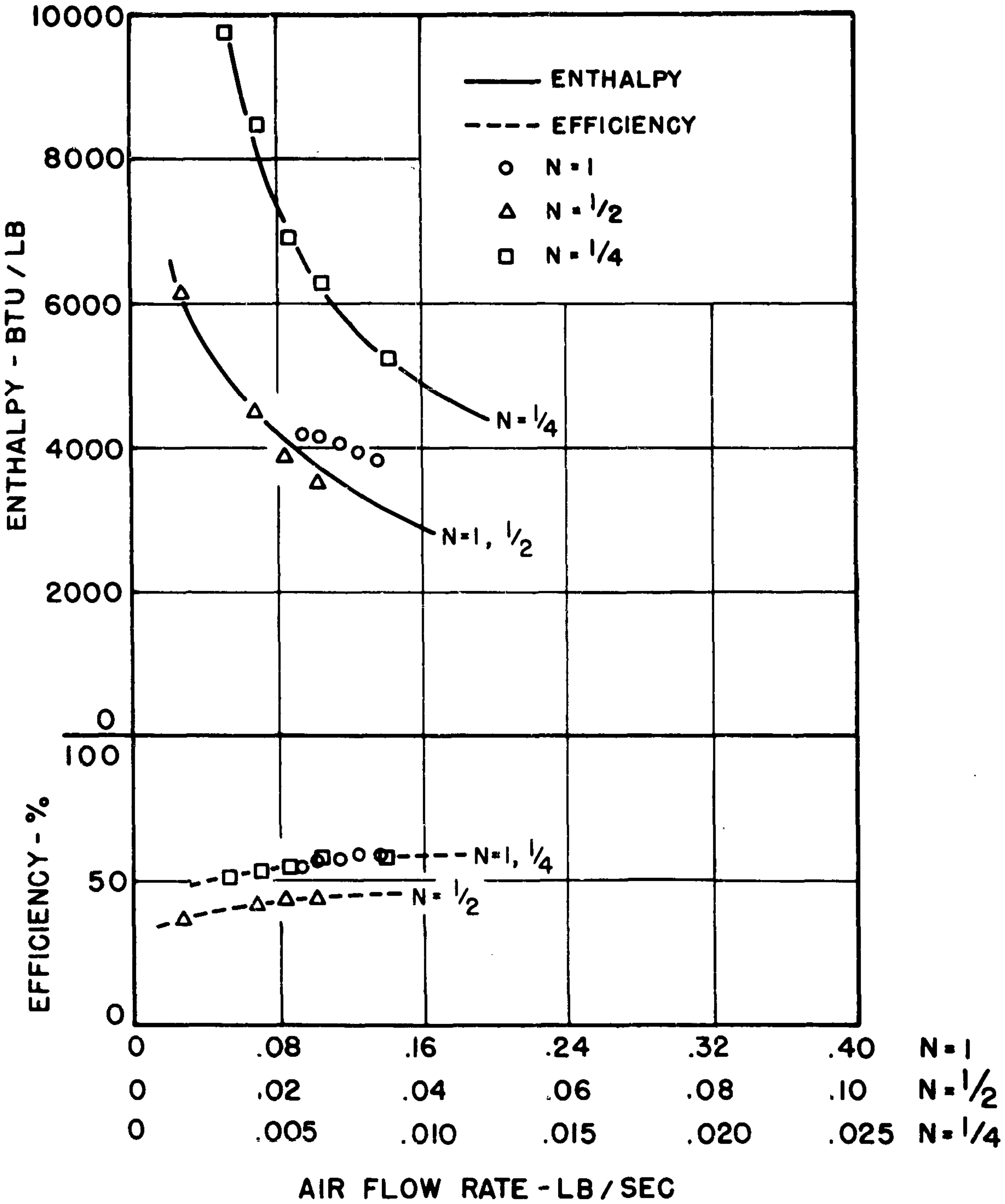


FIGURE 4. SCALING STUDIES (I/N = 800, UNCONSTRICTED)

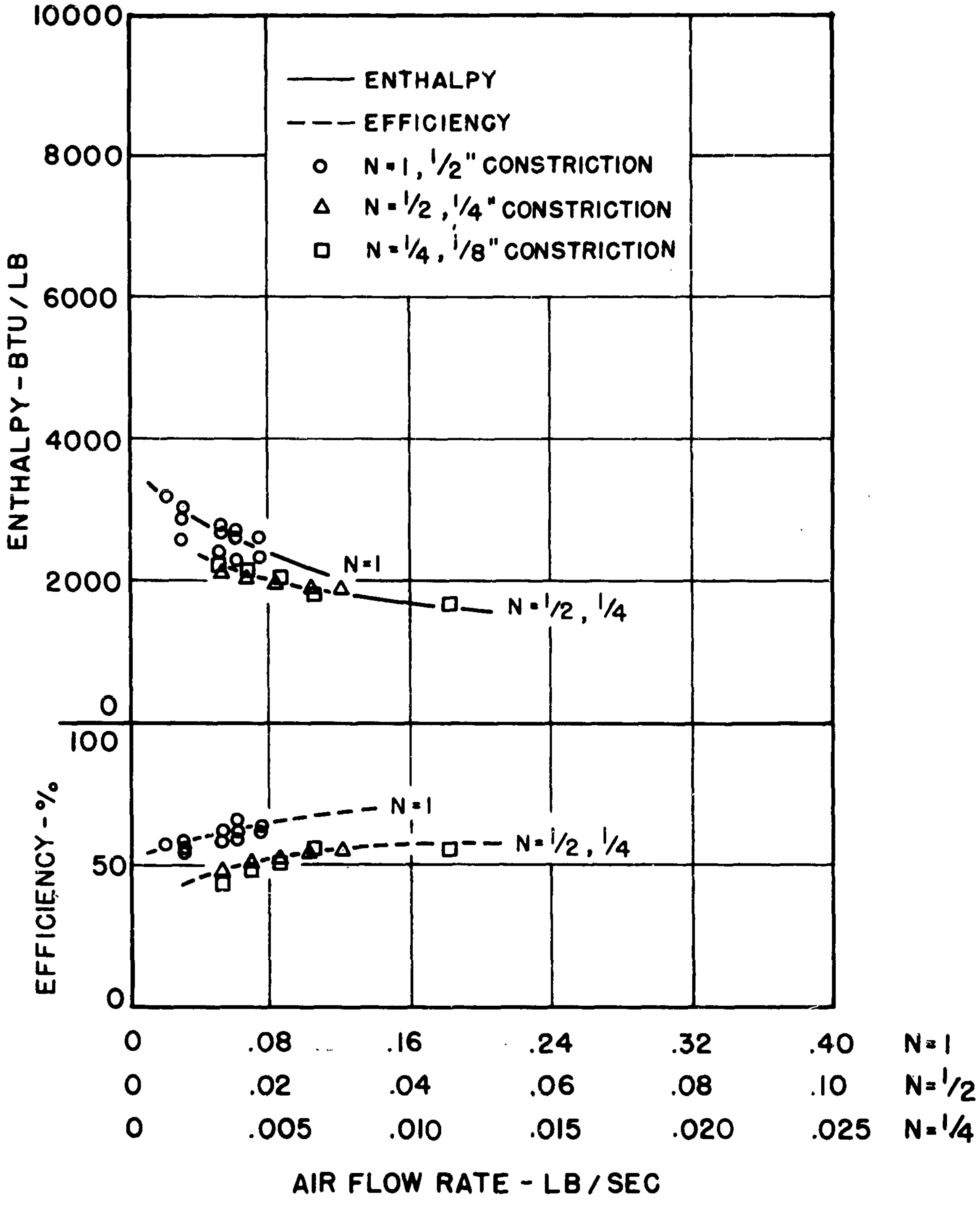


FIGURE 5. SCALING STUDIES (I/N = 200, CONSTRICTED)

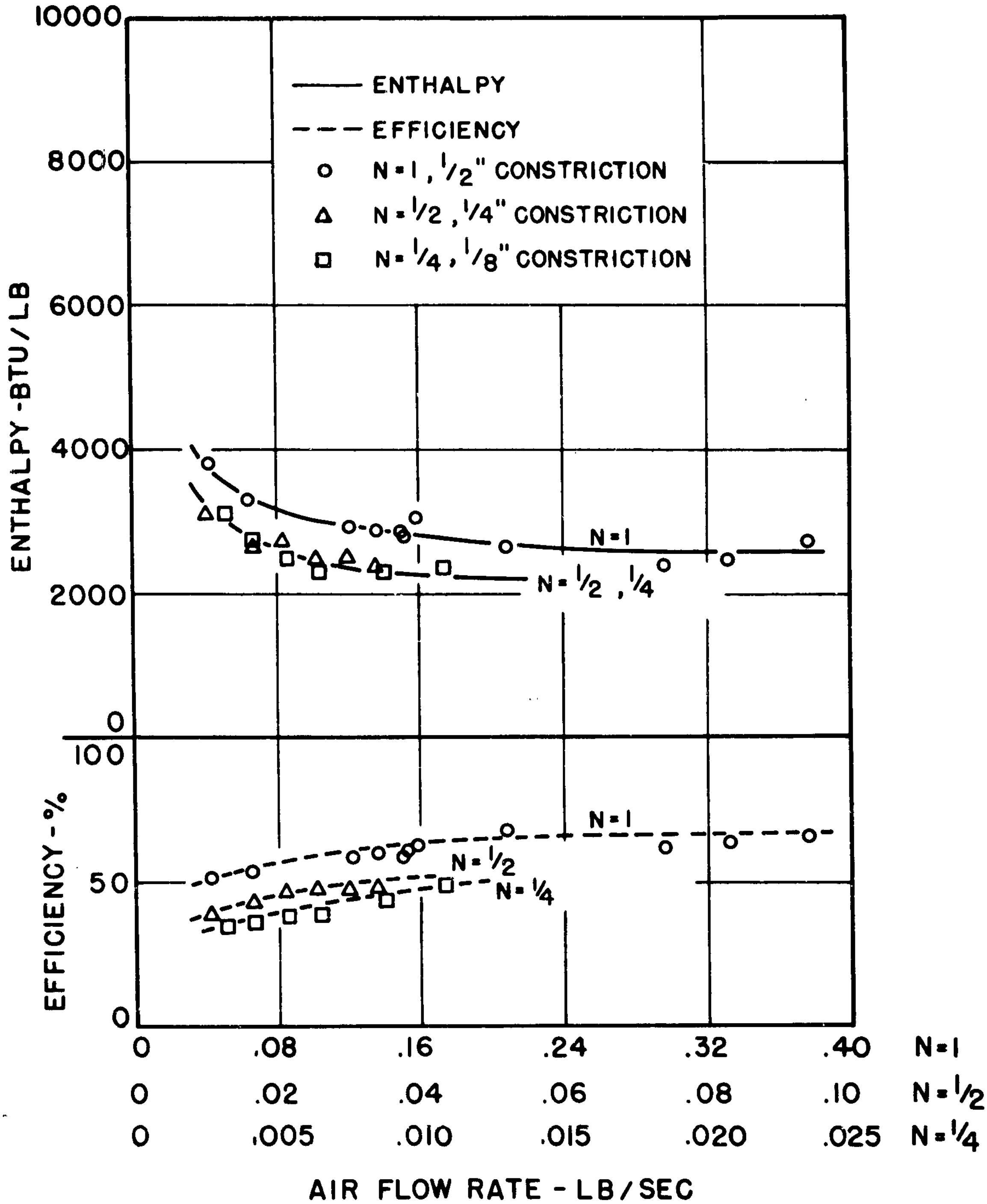


FIGURE 6. SCALING STUDIES (I/N = 400, CONSTRICTED)

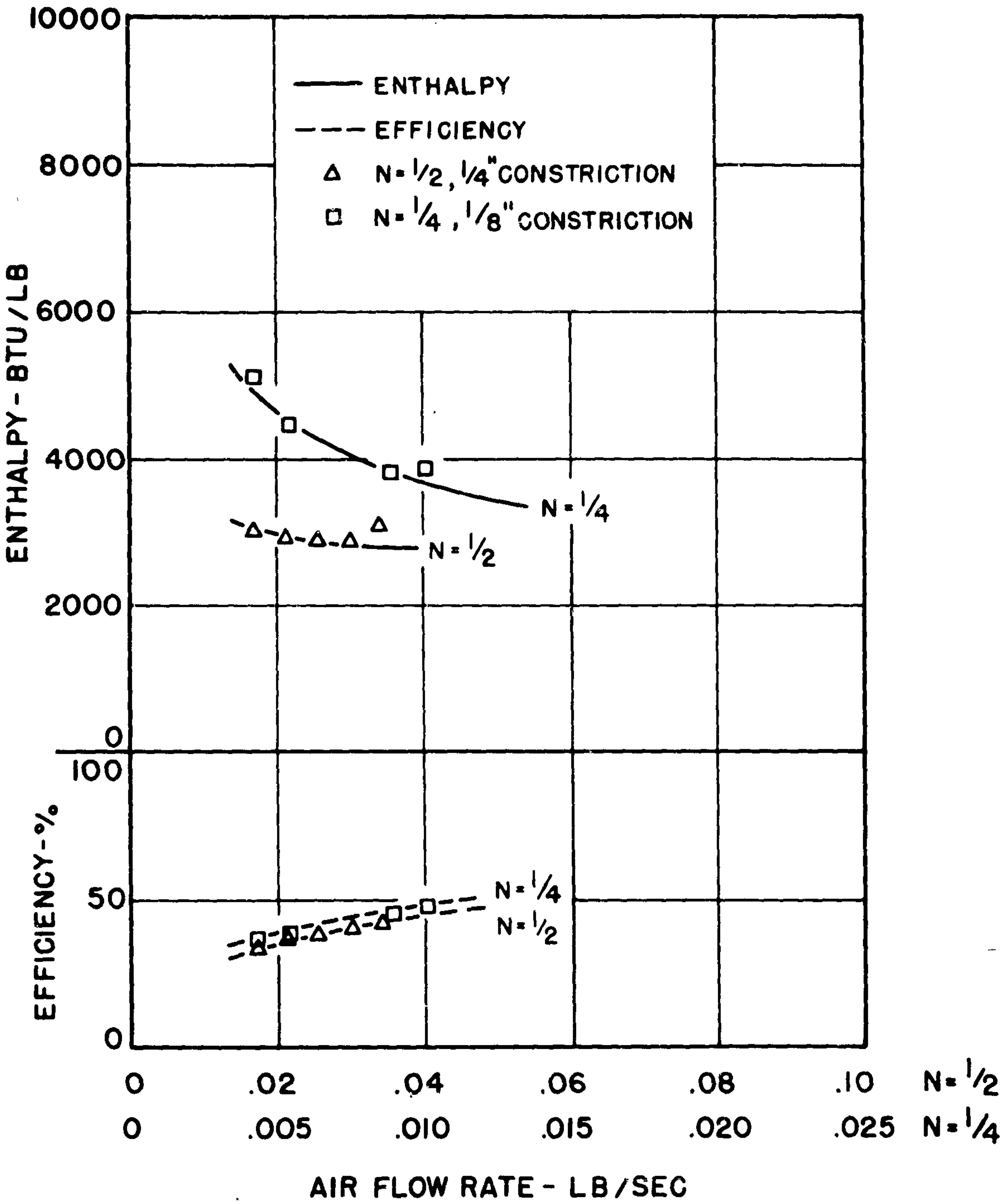
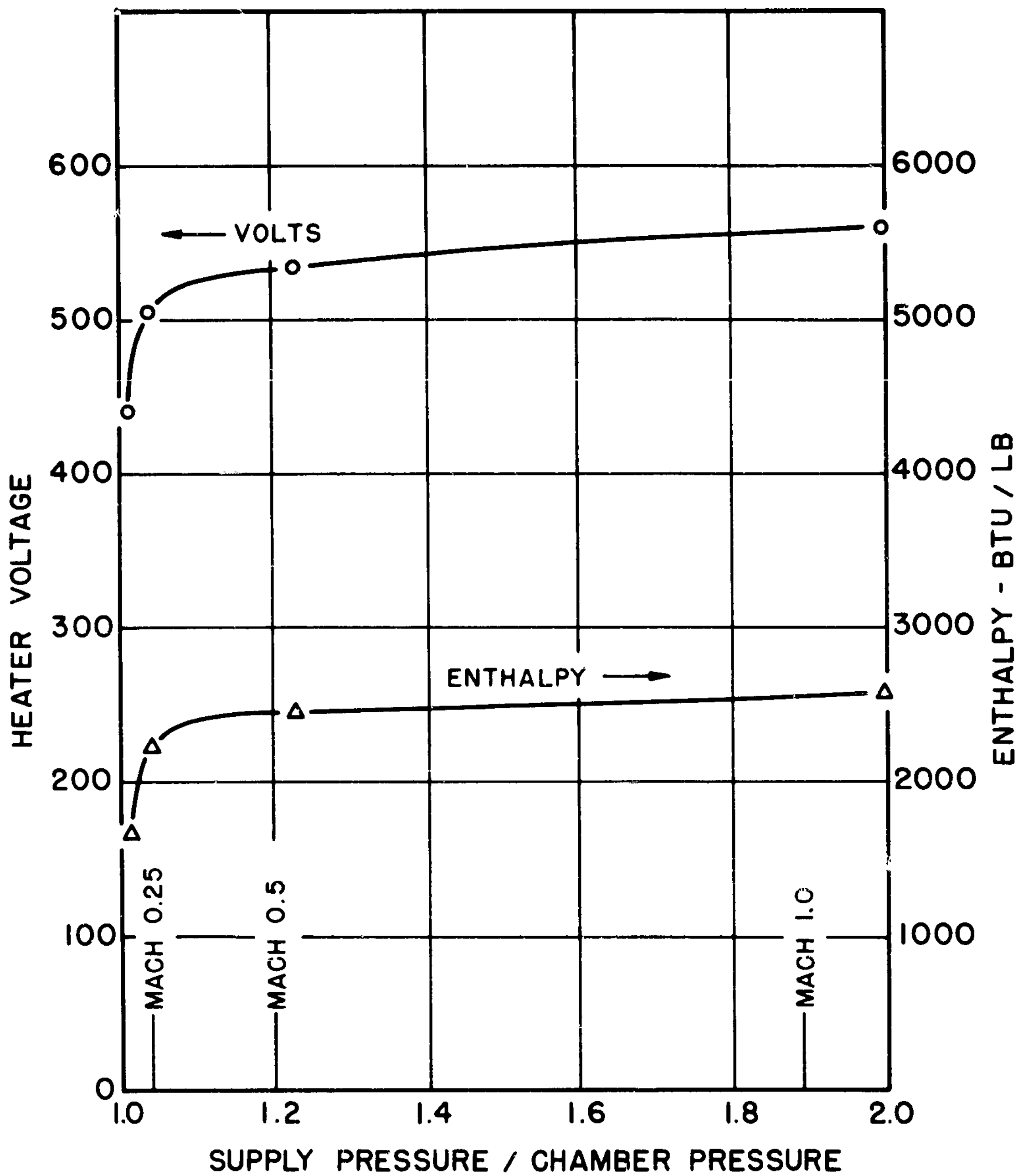
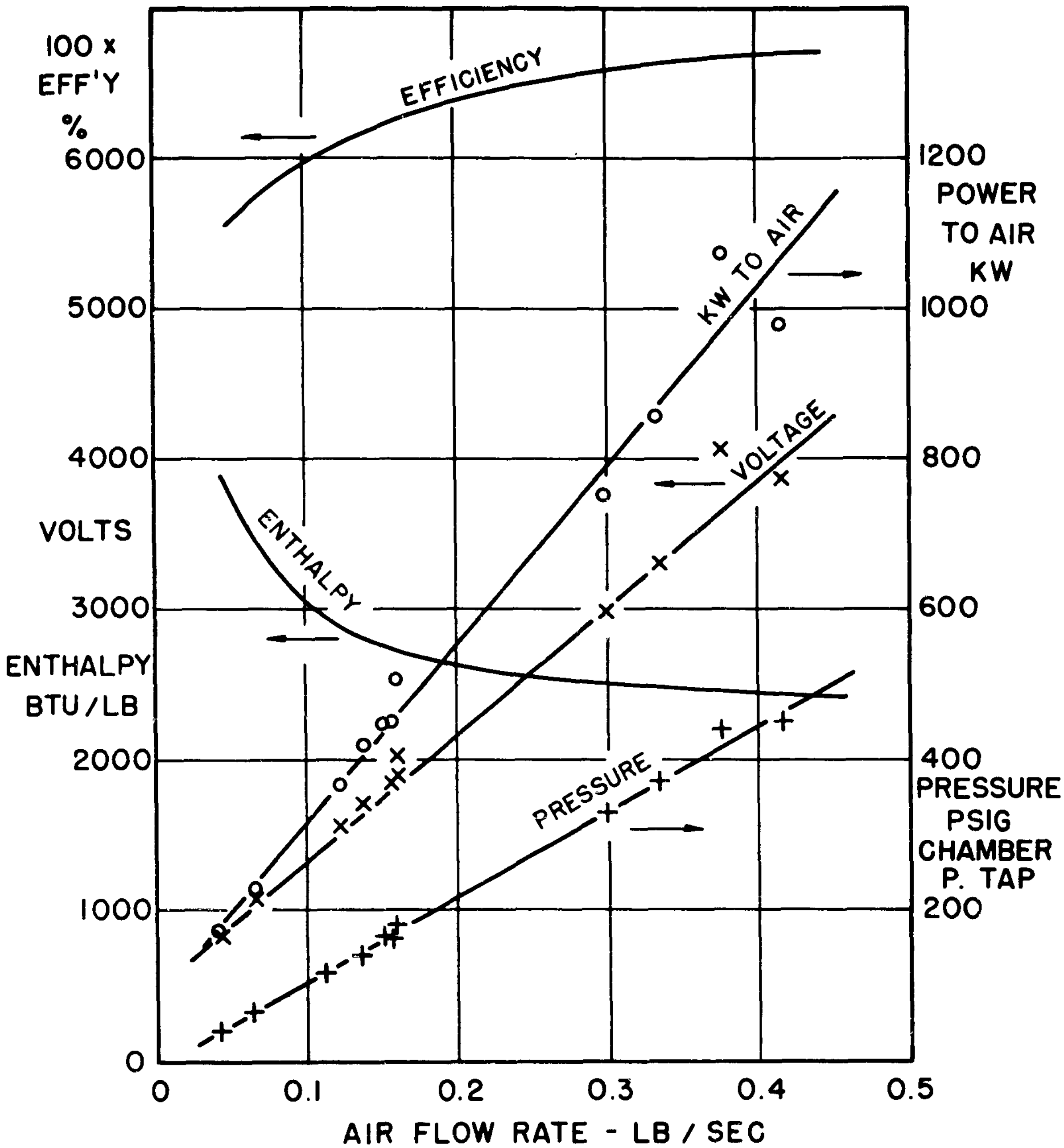


FIGURE 7. SCALING STUDIES (I/N = 800, CONSTRICTED)



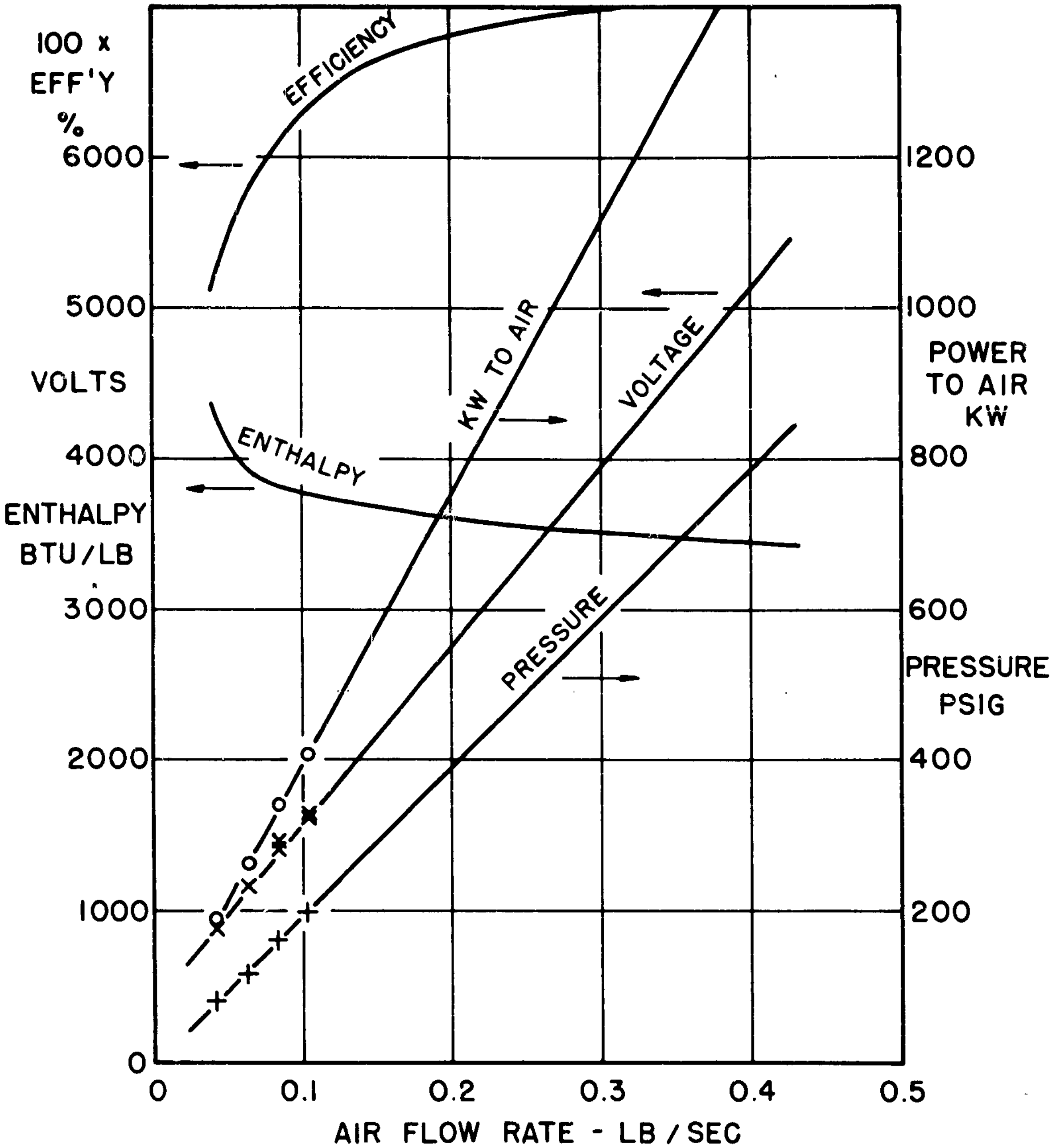
The data were obtained with the quarter-scale heater using a 1/8" diameter nozzle constriction, an arc current of 100 amperes, and an air flow rate of 0.011 lb/sec.

FIGURE 8. EFFECT OF AIR INLET PRESSURE RATIO ON PERFORMANCE



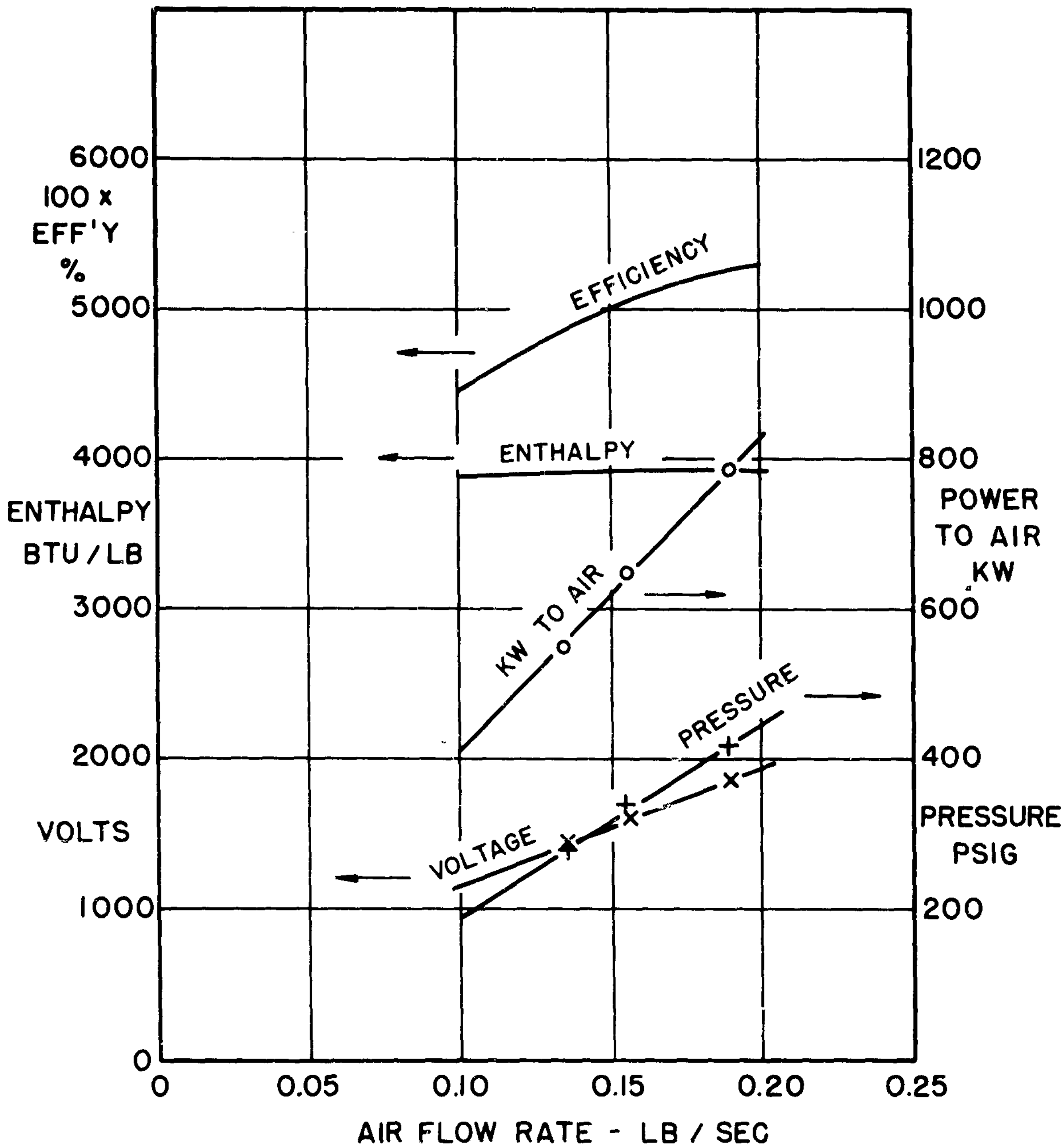
The data were obtained with a 1/2" diameter nozzle constriction and 400 ampere arc current. Curves for enthalpy and efficiency were calculated from smoothed curves of arc voltage and power to the air.

FIGURE 9. MODEL 120 HEATER CHARACTERISTICS (400 AMP, 1/2" CONSTRICTION)



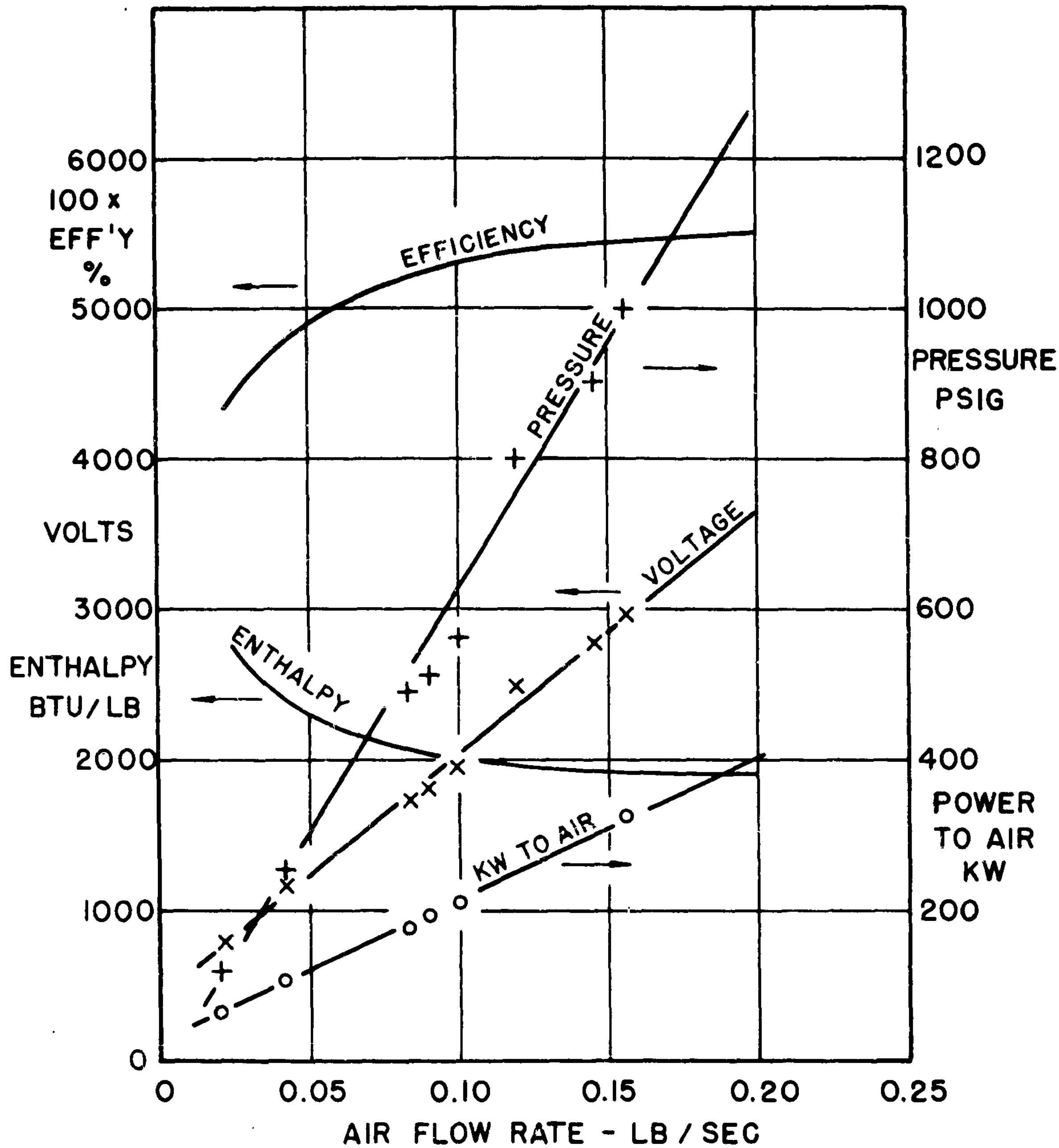
The data were obtained with a 3/8" diameter nozzle constriction and 400 ampere arc current. A shorter than standard nozzle electrode was used. Curves of efficiency and enthalpy were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 10. MODEL 120 HEATER CHARACTERISTICS (400 AMP, 3/8" CONSTRICTION)



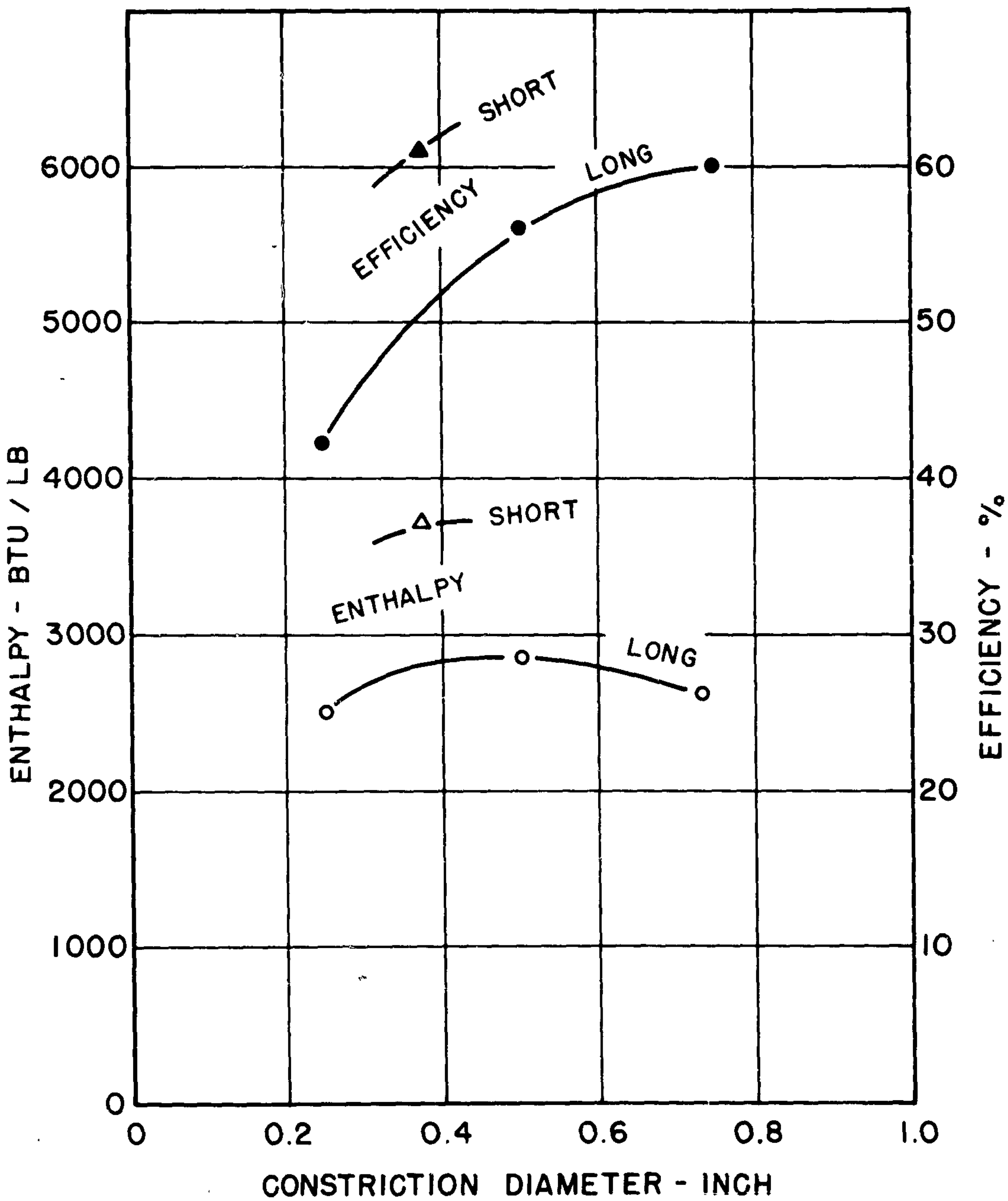
The data were obtained with a 3/8" diameter nozzle constriction and 800 ampere arc current. A shorter than standard nozzle electrode was used. Curves of efficiency and enthalpy were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 11. MODEL 120 HEATER CHARACTERISTICS (800 AMP, 3/8" CONSTRICTION)



The data were obtained with a 3/16" diameter nozzle constriction and 200 ampere arc current. A shorter than standard nozzle electrode was used. Curves for efficiency and enthalpy were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 12. MODEL 120 HEATER CHARACTERISTICS (200 AMP, 3/16" CONSTRICTION)



The data were obtained with an arc current of 400 amperes and an air flow rate of 0.104 Lb/sec.

FIGURE 13. EFFECT OF NOZZLE ELECTRODE LENGTH - MODEL 120

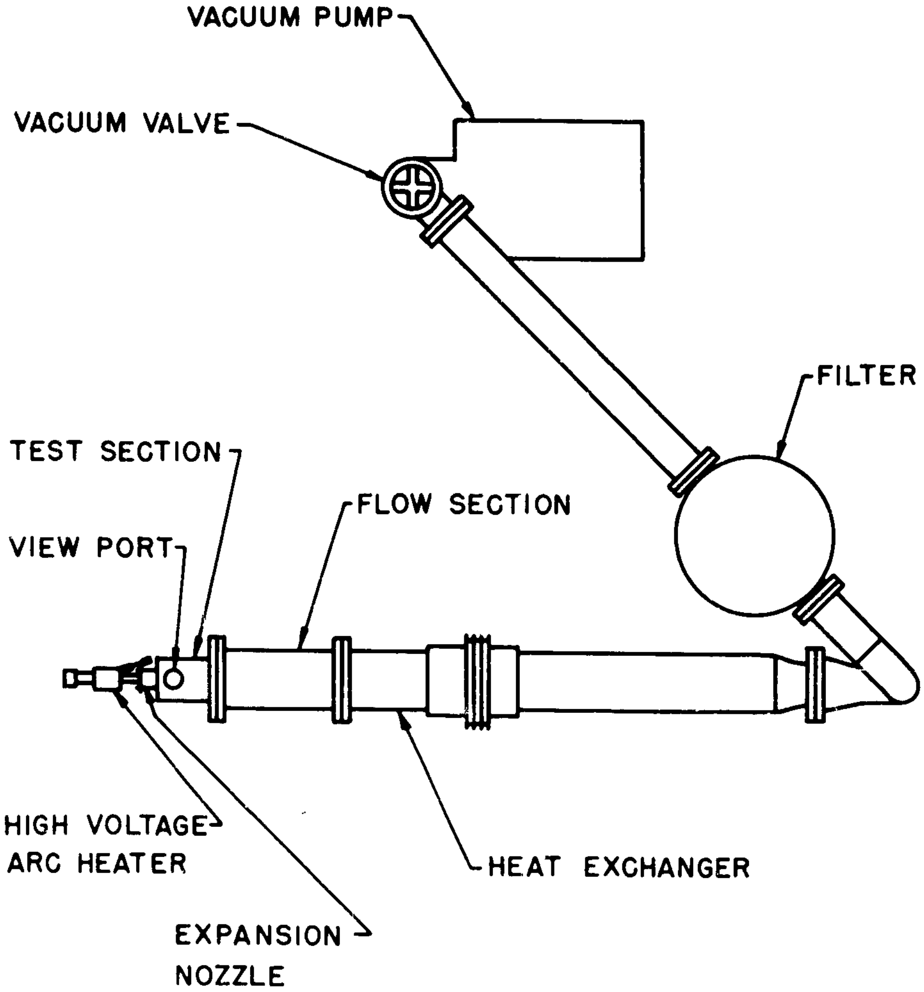


FIGURE 14. DIAGRAM OF WIND TUNNEL

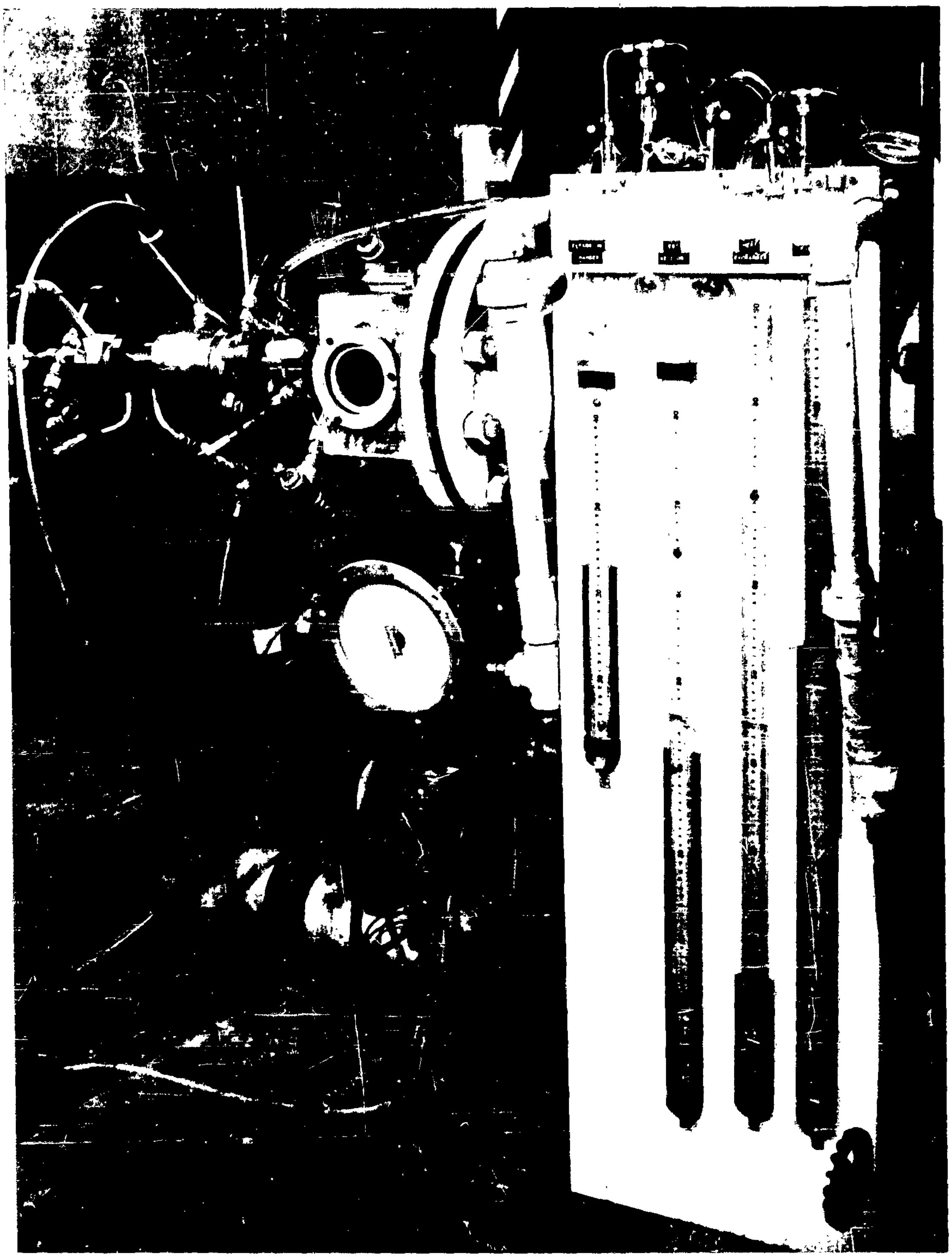
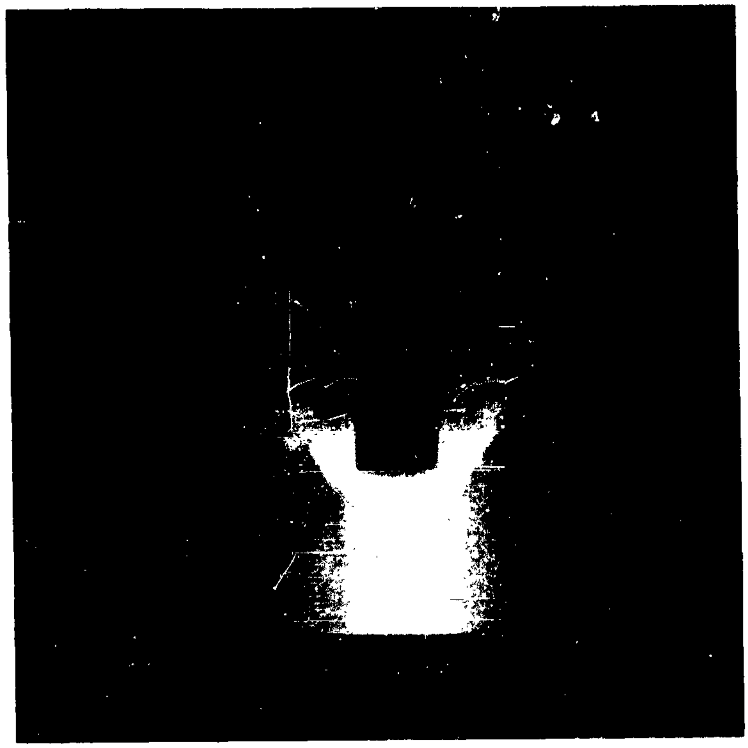


Figure 15. Wind Tunnel Photograph



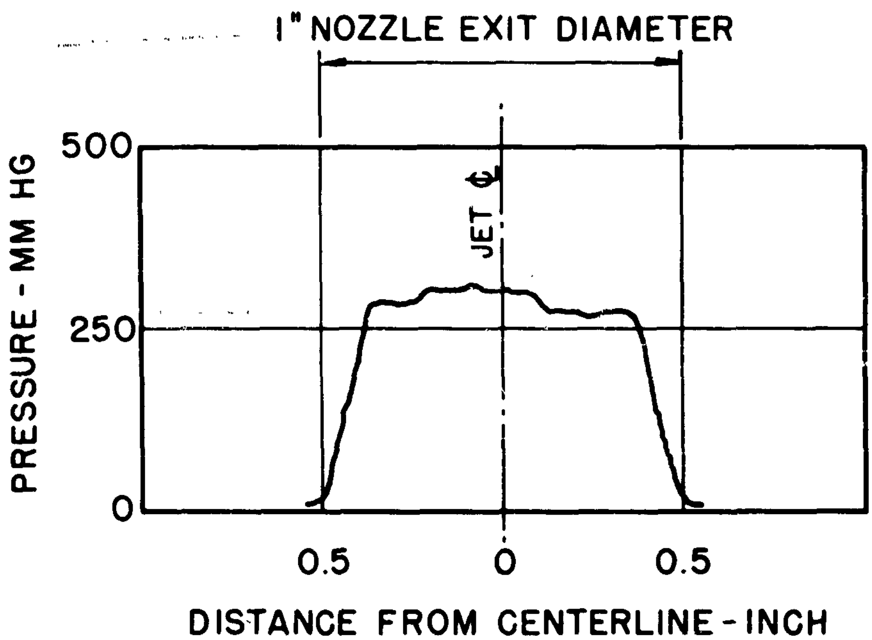


FIGURE 16. WIND TUNNEL STAGNATION PRESSURE PROBE AND TRAVERSE

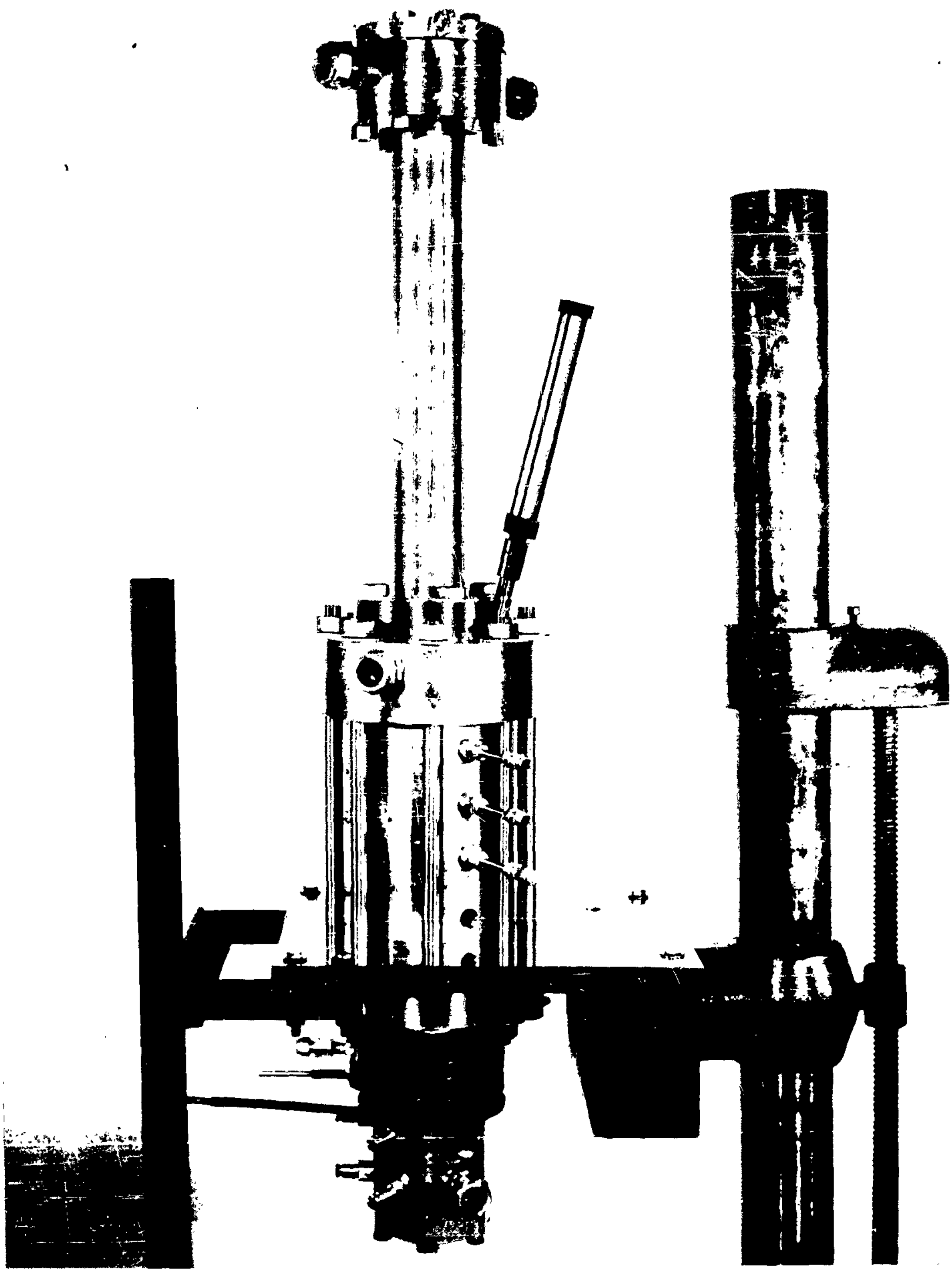
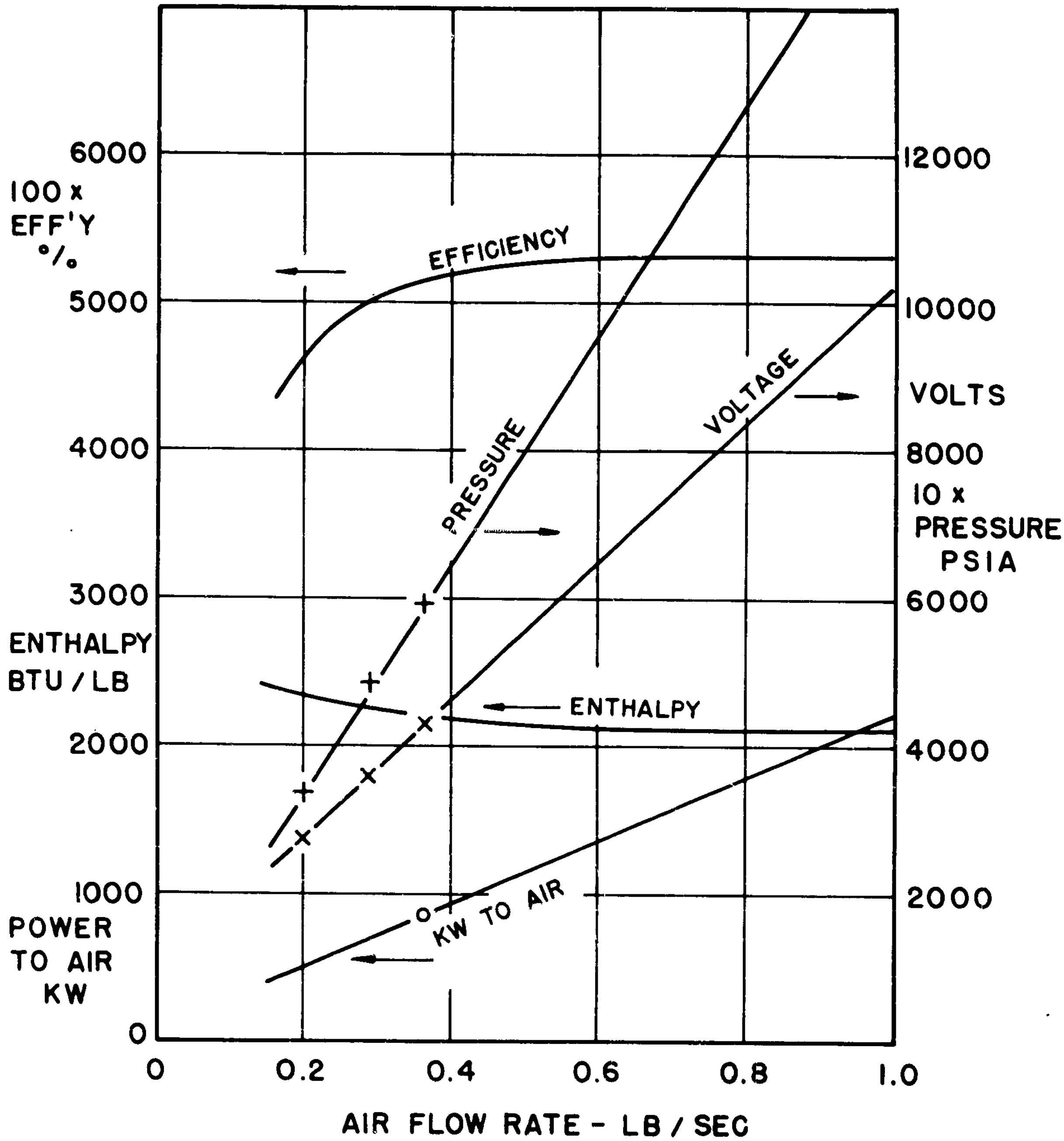
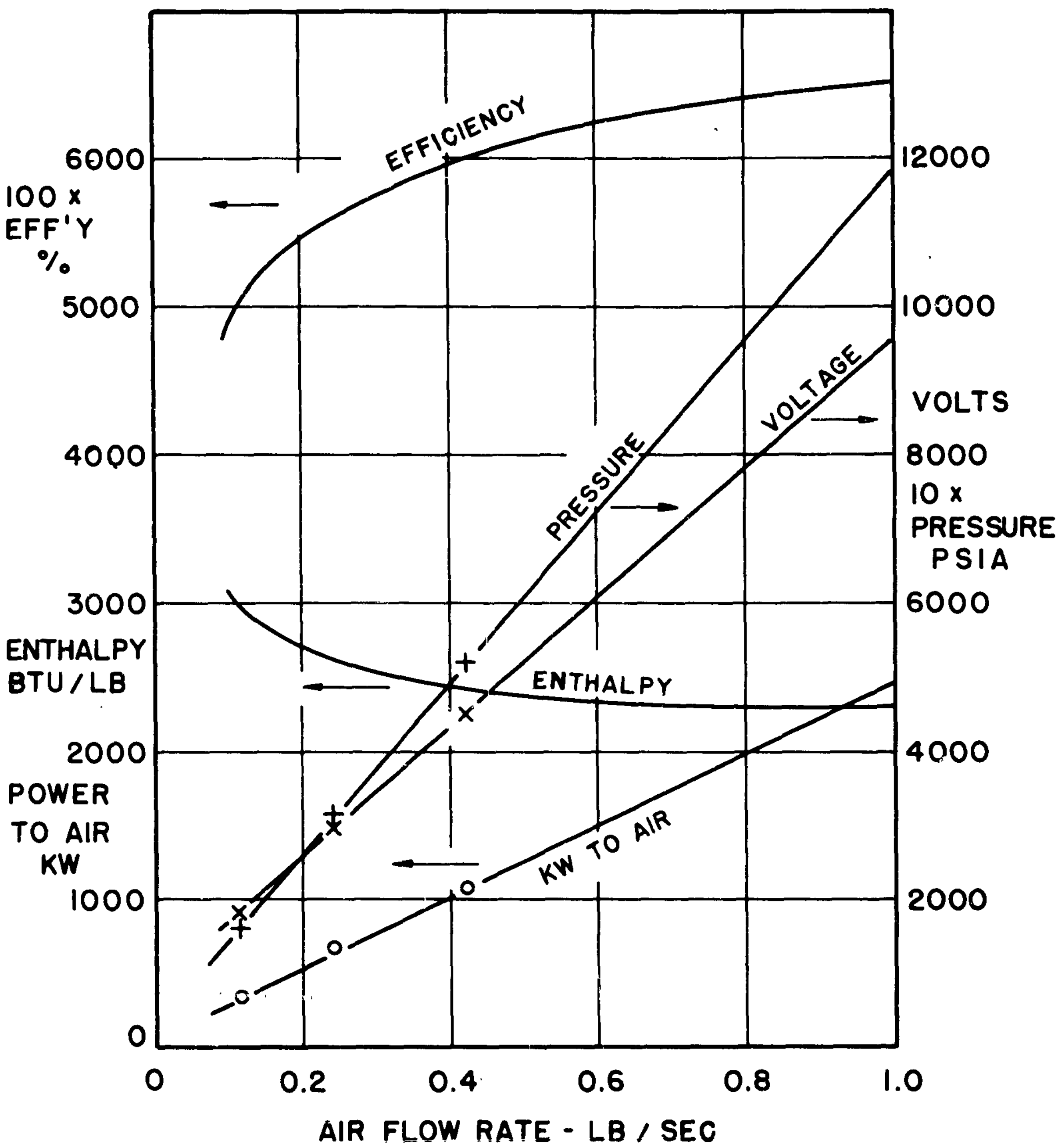


Figure 17. Model 124 High Voltage Arc Air Heater



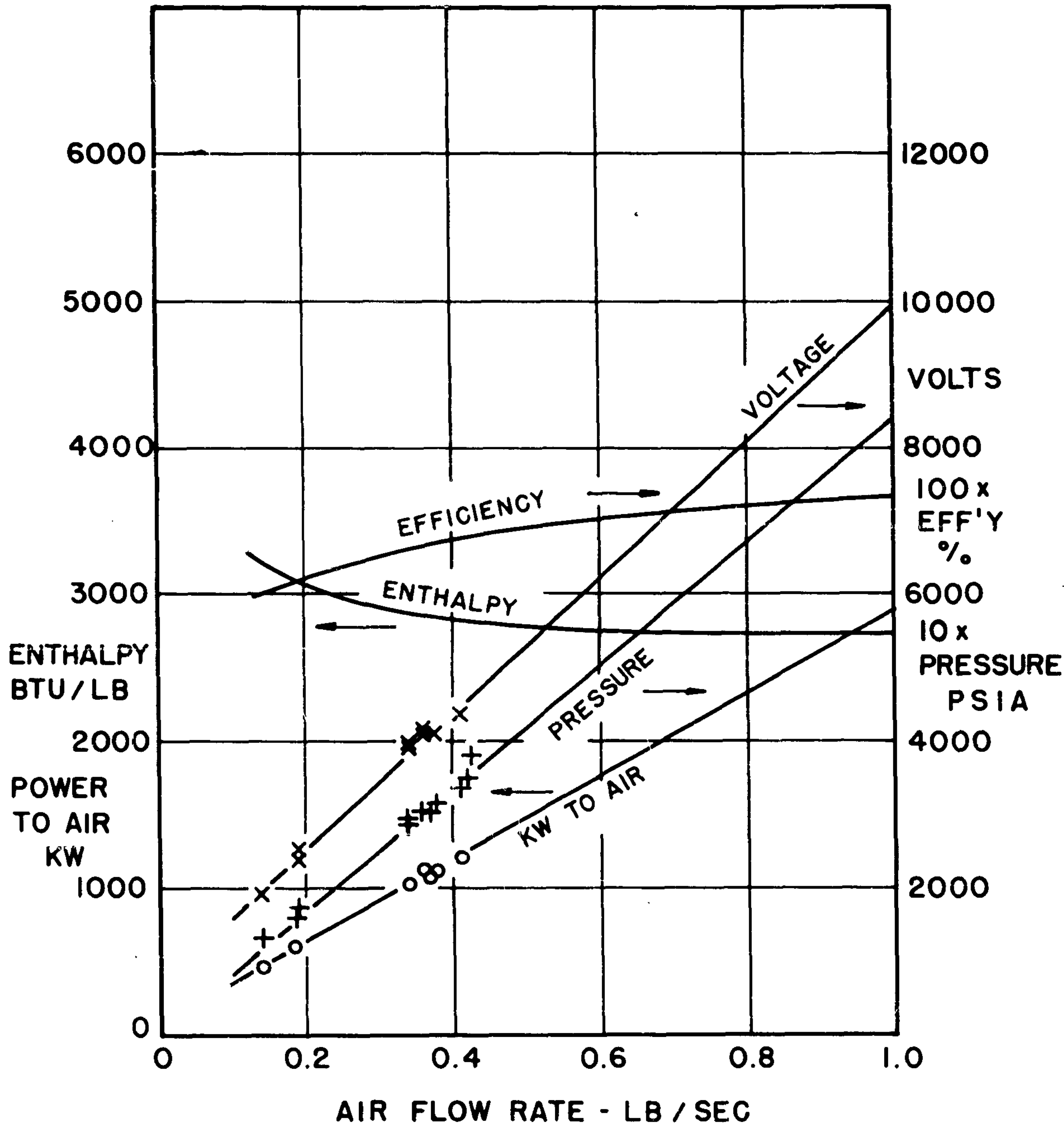
The data were obtained with a 3/8" diameter nozzle constriction and 400 ampere arc current. Enthalpy and efficiency were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 18. MODEL 124 HEATER CHARACTERISTICS (400 AMP, 3/8" CONSTRICTION)



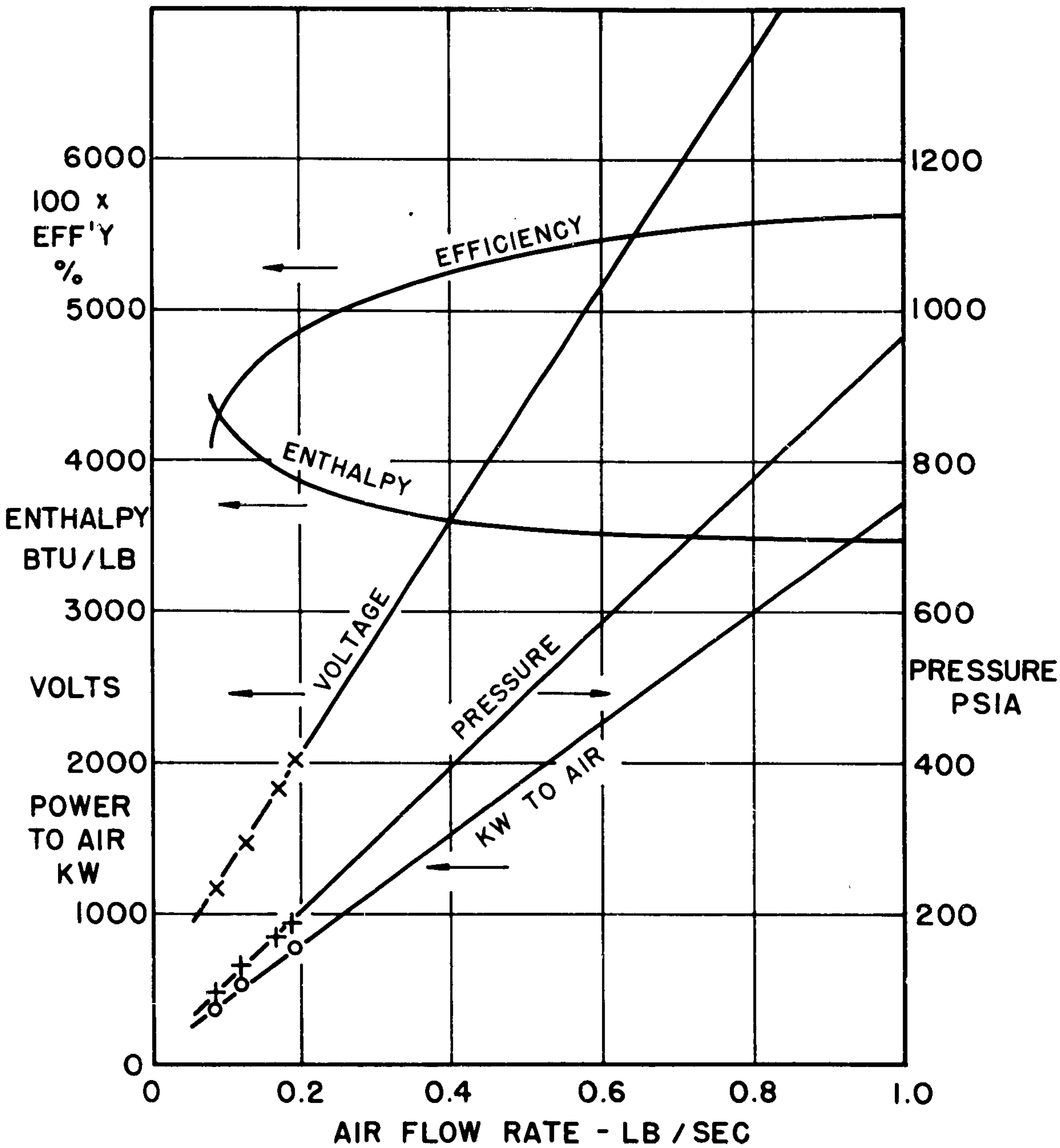
The data were obtained with a 7/16" diameter nozzle constriction and 400 ampere arc current. Efficiency and enthalpy were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 19. MODEL 124 HEATER CHARACTERISTICS (400 AMP, 7/16" CONSTRICTION)



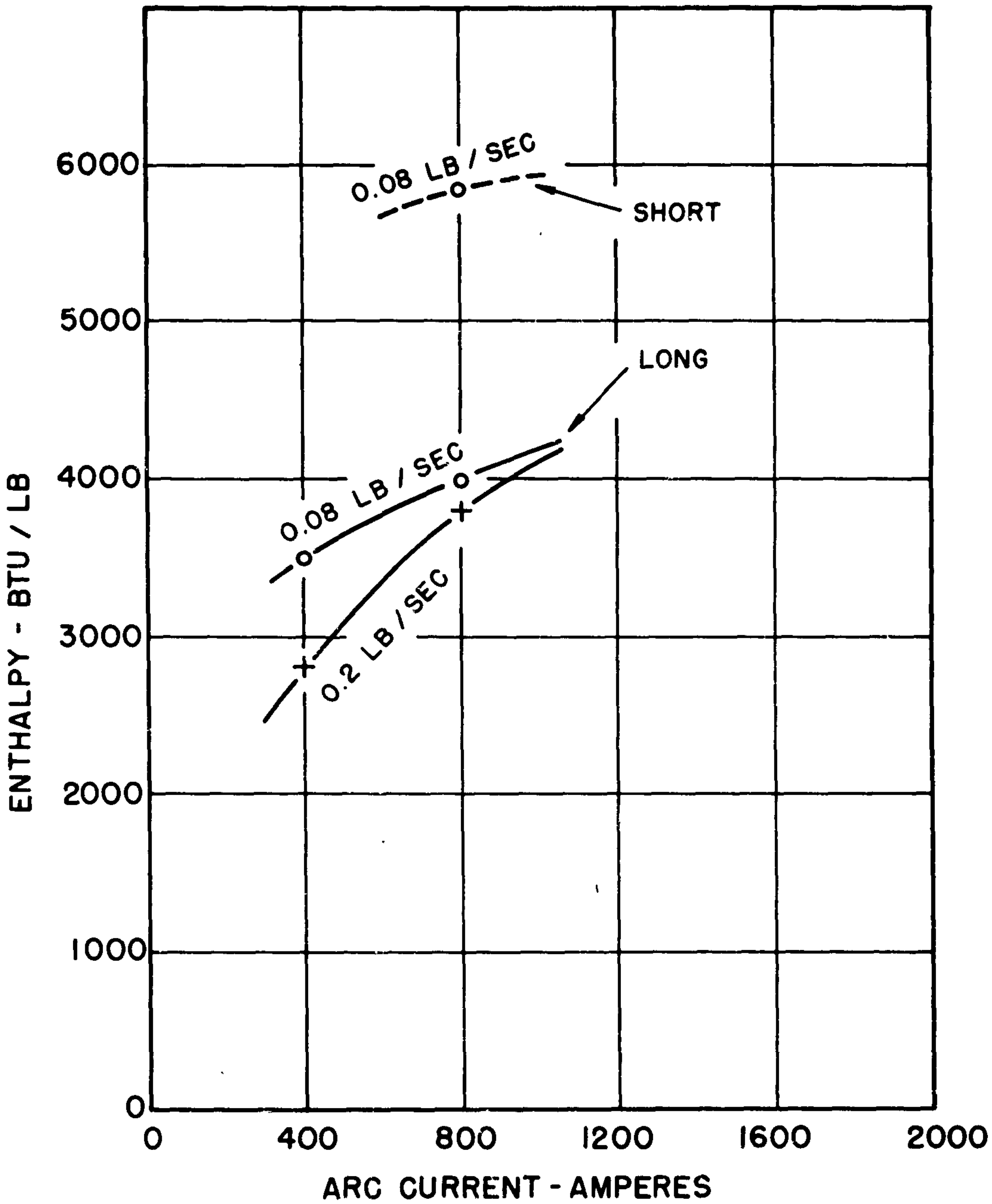
The data were obtained with a 0.525" diameter nozzle constriction and 400 ampere arc current. Efficiency and enthalpy were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 20. MODEL 124 HEATER CHARACTERISTICS (400 AMP, 0.525" CONSTRICTION)



The data were obtained with a 0.525" diameter nozzle constriction and 800 ampere arc current. Enthalpy and efficiency were calculated from smoothed curves for arc voltage and power to the air.

FIGURE 21. MODEL 124 HEATER CHARACTERISTICS (800 AMP, 0.525" CONSTRICTION)



The data were obtained with a 0.525" diameter nozzle constriction and two different nozzle electrode lengths (corresponding to Model 124A and 124B).

FIGURE 22. EFFECT OF NOZZLE ELECTRODE LENGTH - MODEL 124

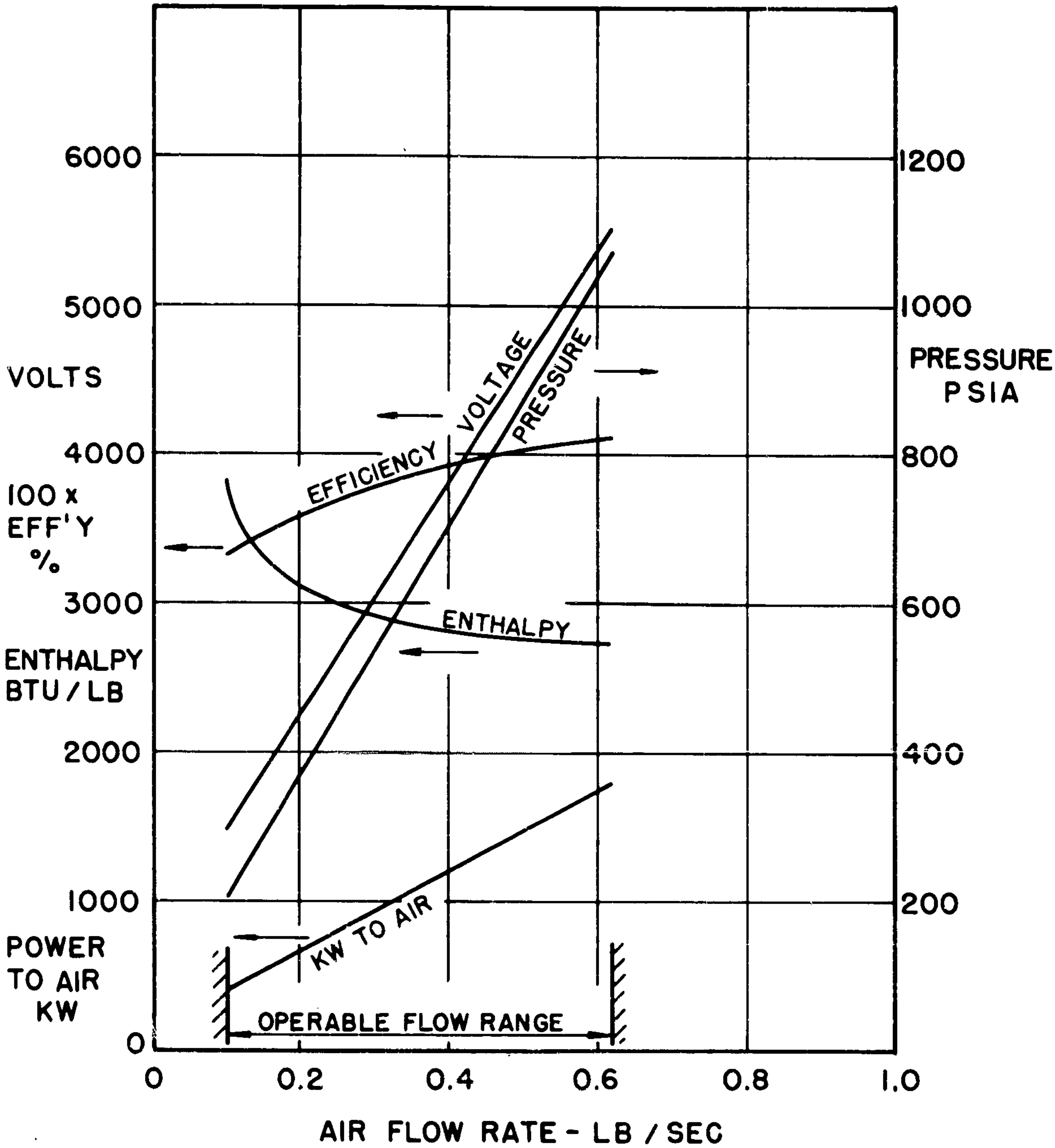


FIGURE 23. MODEL 124 HEATER PREDICTED CHARACTERISTICS
(800 AMP, 3/8" CONSTRICTION)

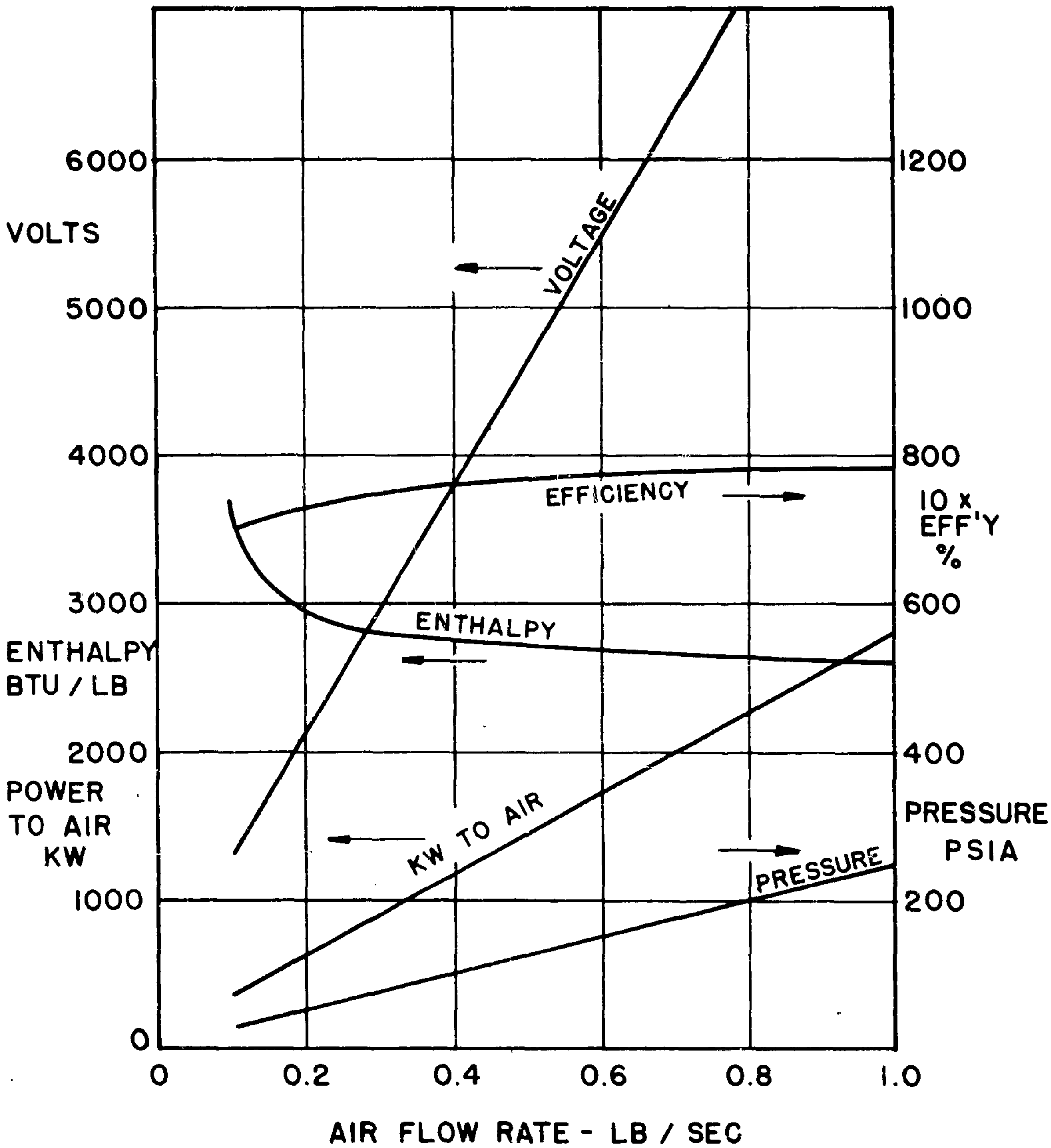


FIGURE 24. MODEL 124 HEATER PREDICTED CHARACTERISTICS
(400 AMP, 1" CONSTRICTION)

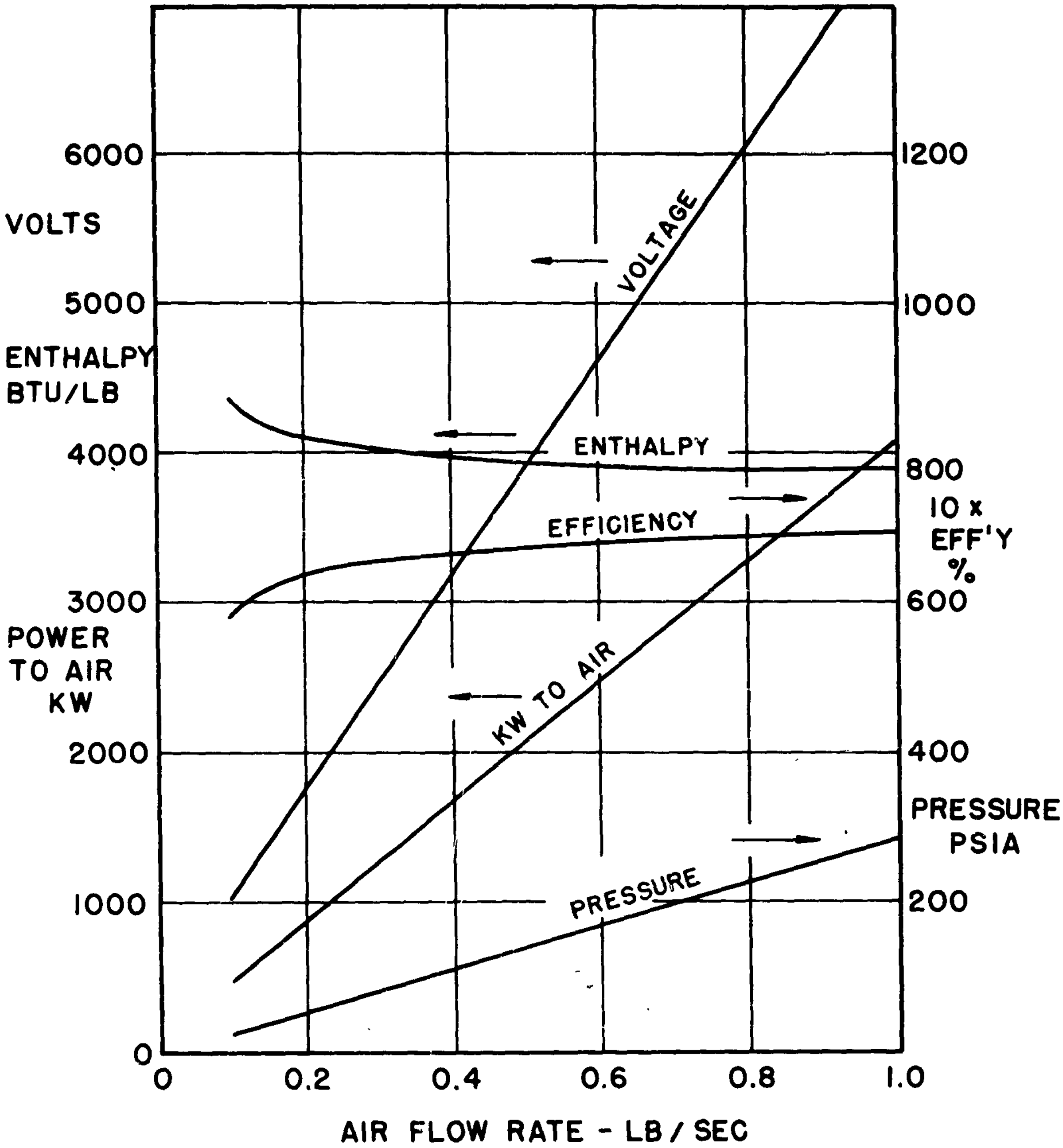


FIGURE 25. MODEL 124 HEATER PREDICTED CHARACTERISTICS
(800 AMP, 1" CONSTRICTION)

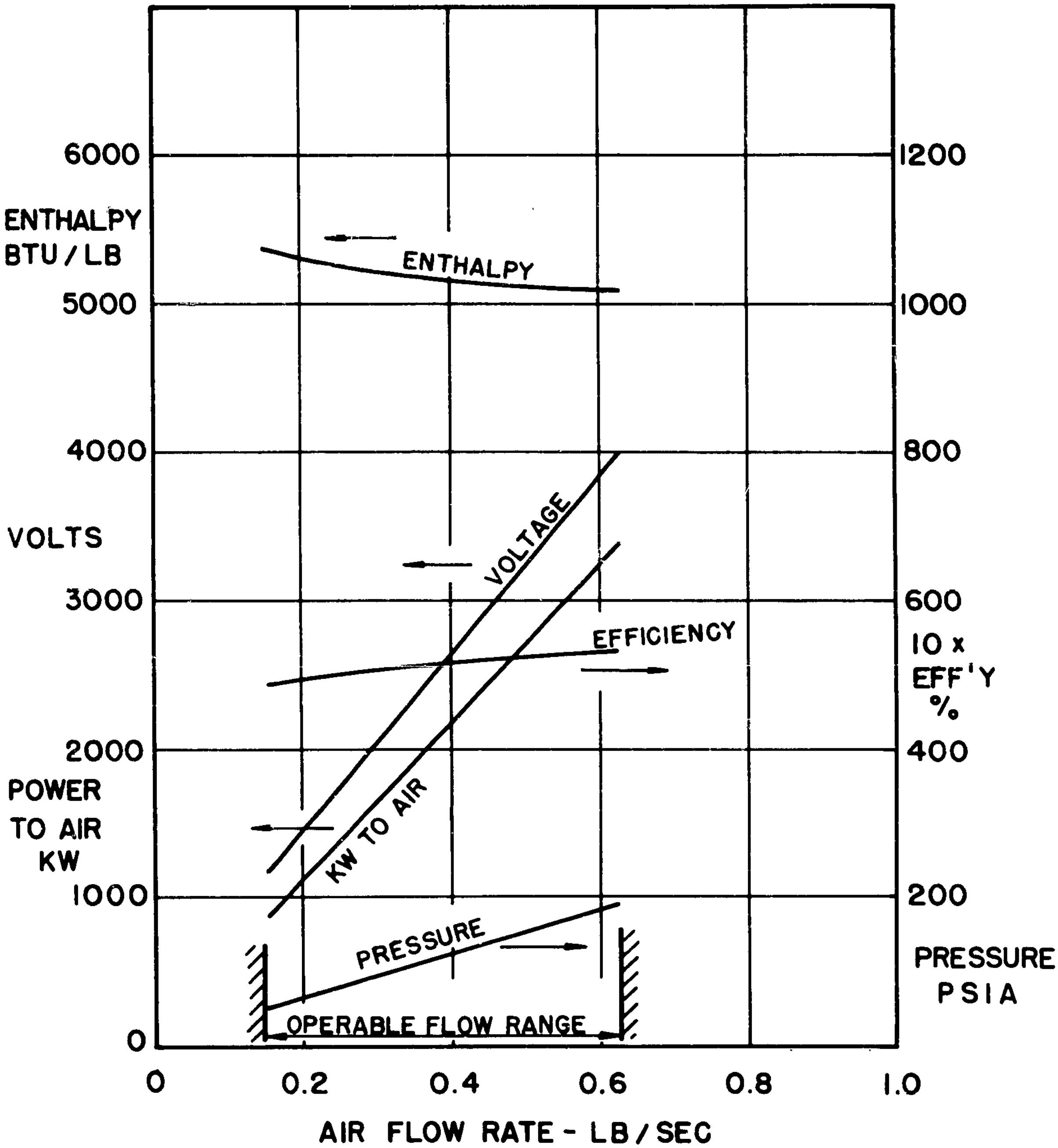


FIGURE 26. MODEL 124 HEATER PREDICTED CHARACTERISTICS
(1600 AMP, 1" CONSTRICTION)

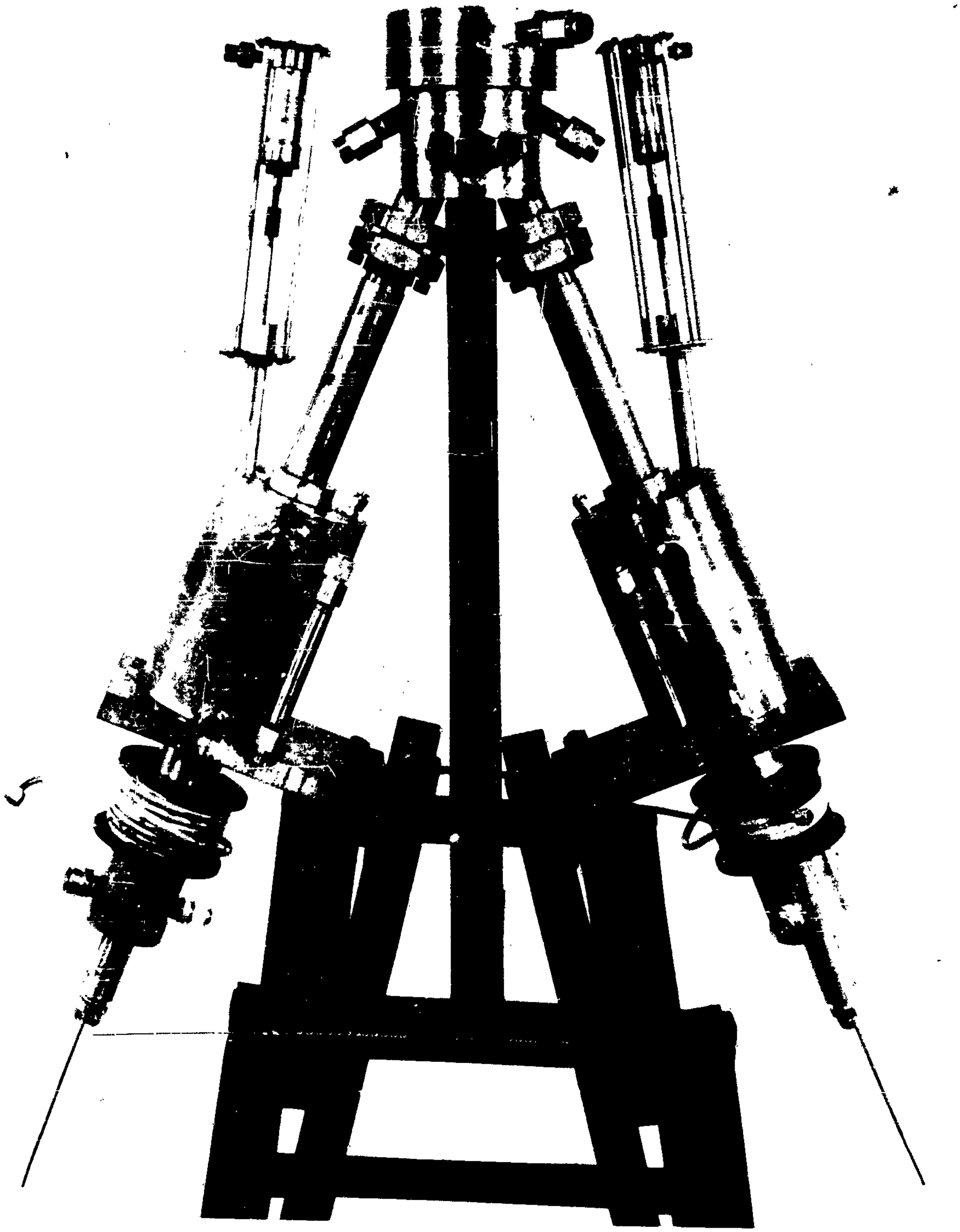
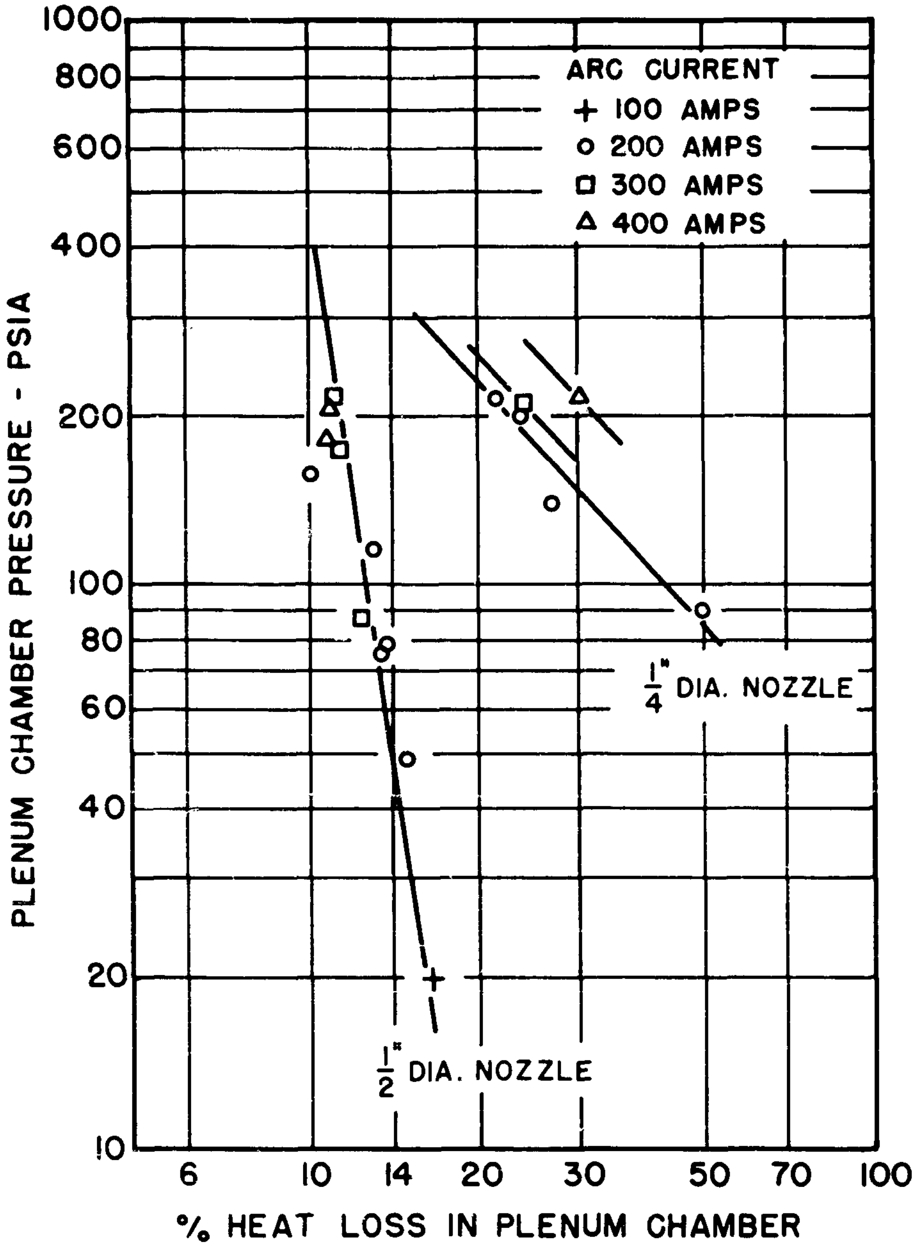


Figure 27. Dual Heater Nozzle



The data were obtained with two Model 120 heaters discharging into a common plenum having a constricting nozzle at its exit. The current tabulated is that to each heater. The abscissa is the percentage of heat in the gas entering the plenum which was lost to the plenum cooling water.

FIGURE 28. PLENUM CHAMBER HEAT LOSS

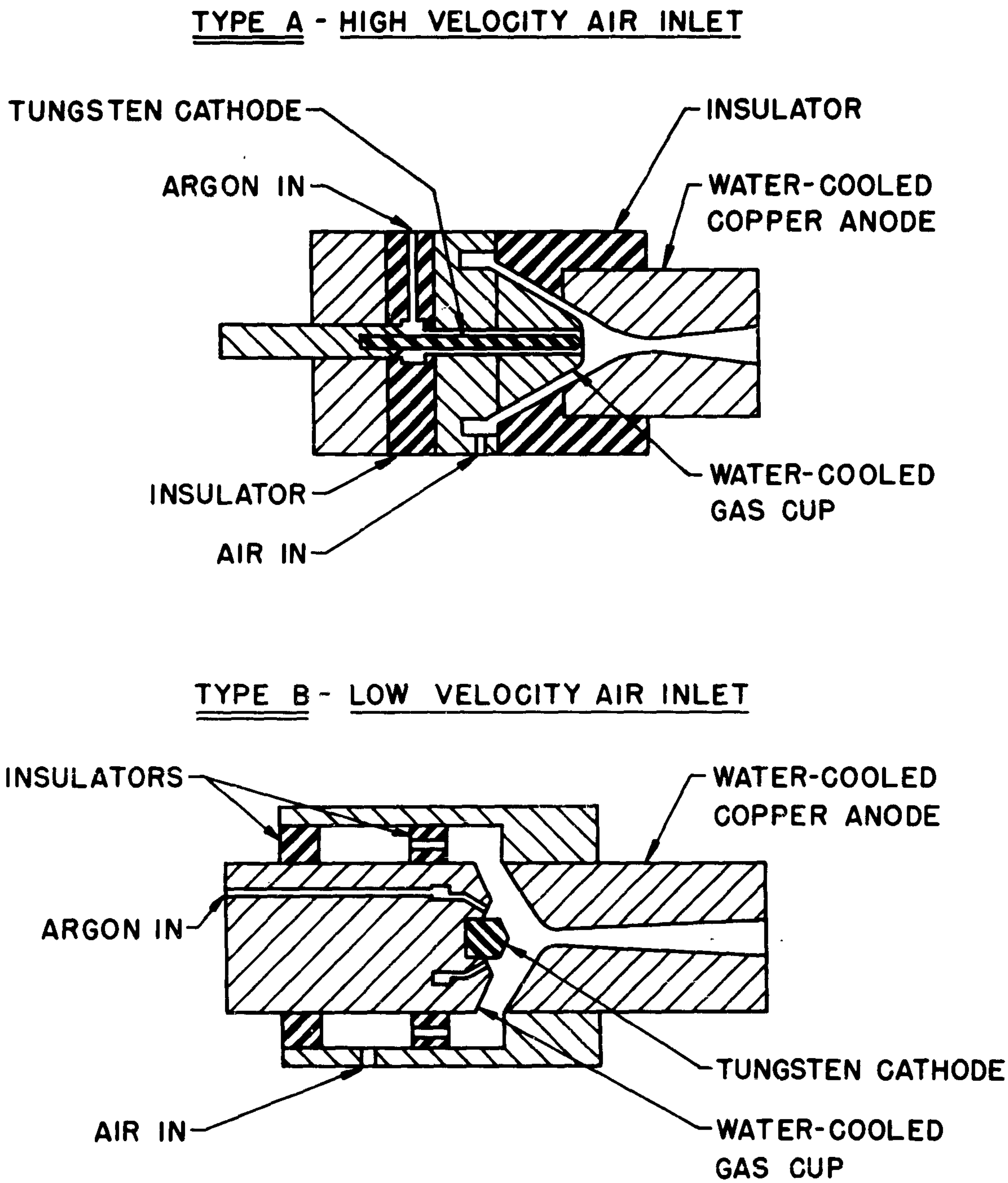


FIGURE 29. DIRECT ARC HEATER SCHEMATIC DIAGRAMS

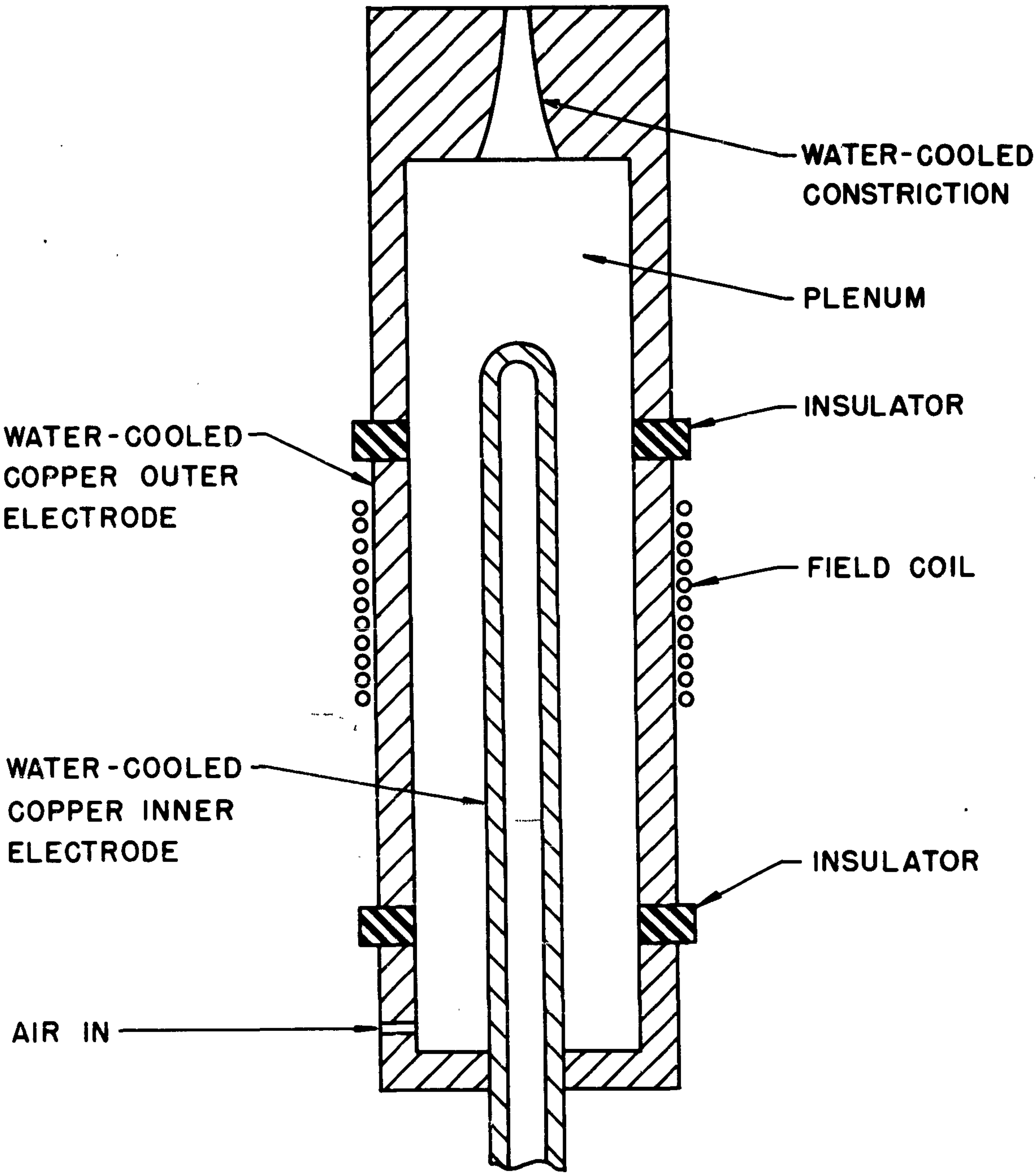


FIGURE 30. TOROIDAL ARC HEATER SCHEMATIC DIAGRAM

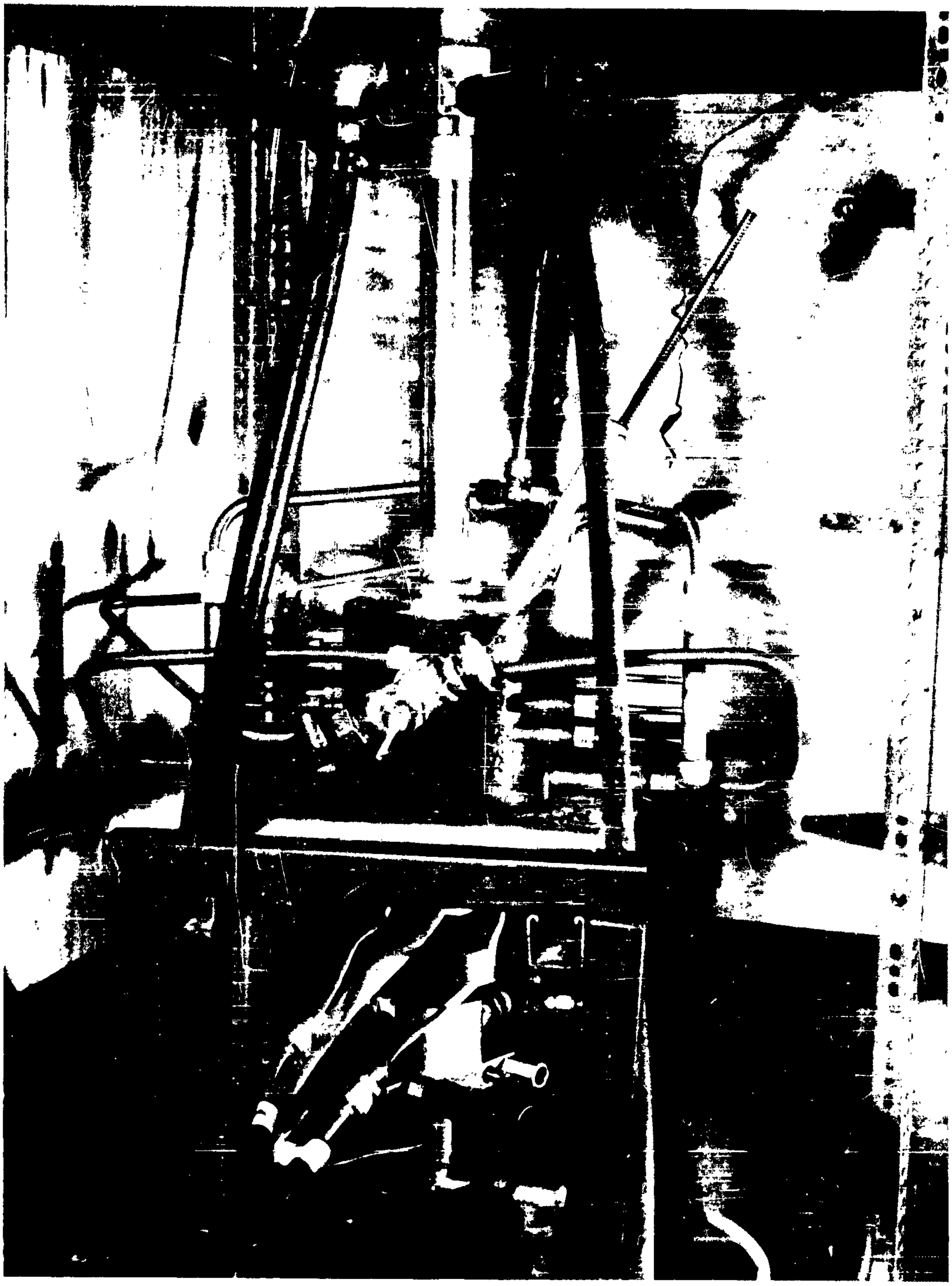


Figure 31. Model 118 High Voltage Arc Heater

Figure 32. Model 112 Direct Arc Heater

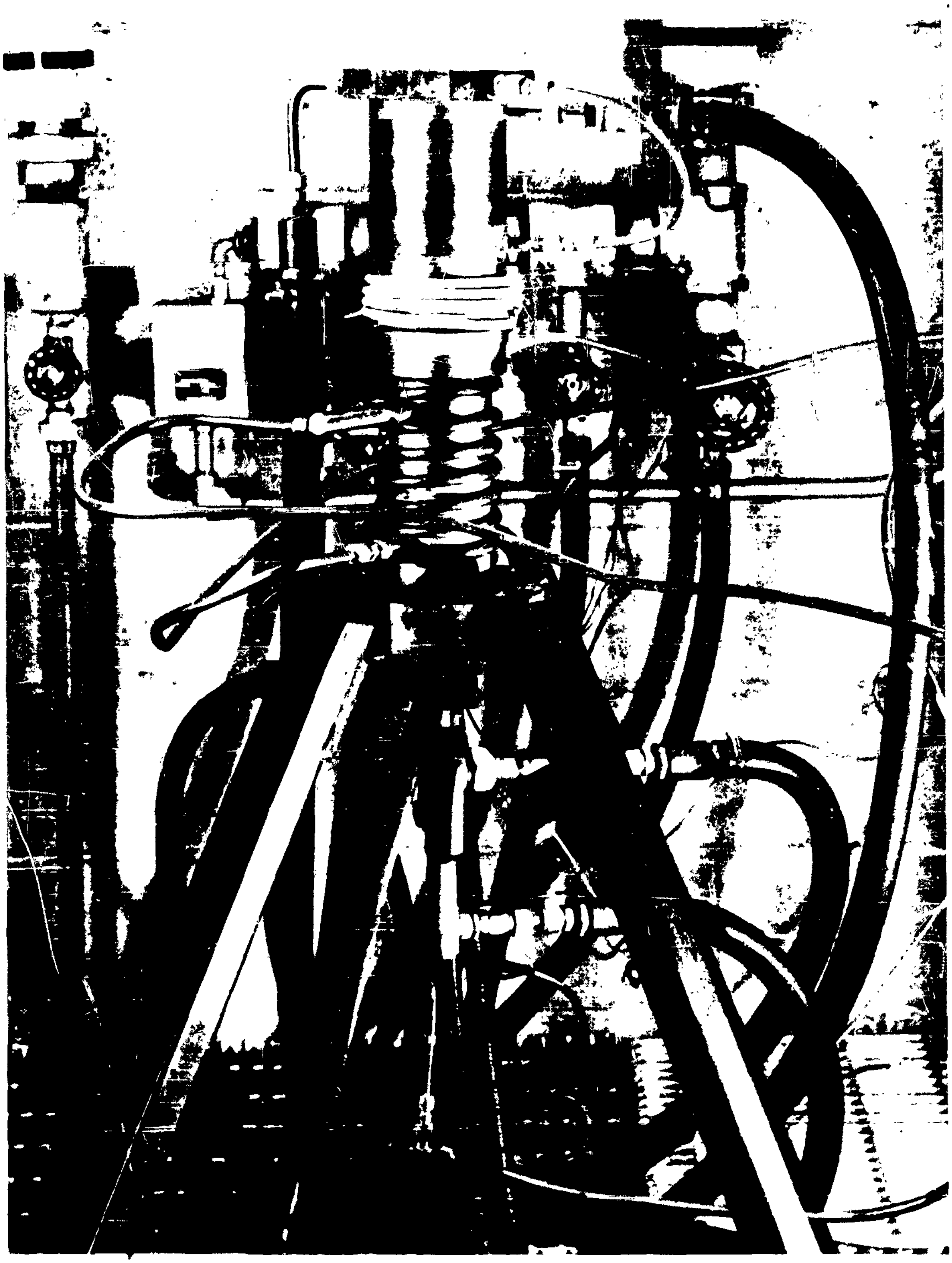
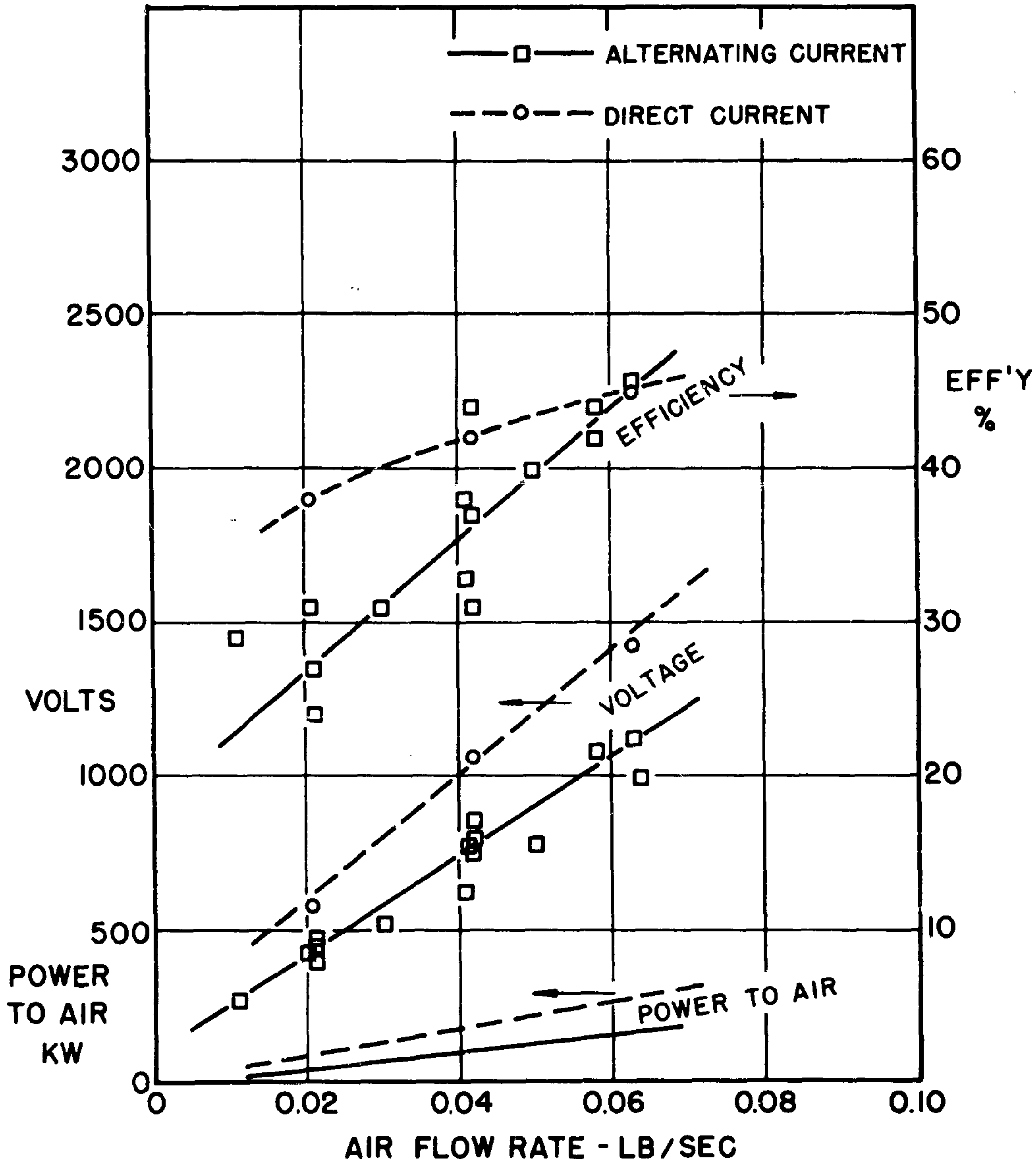
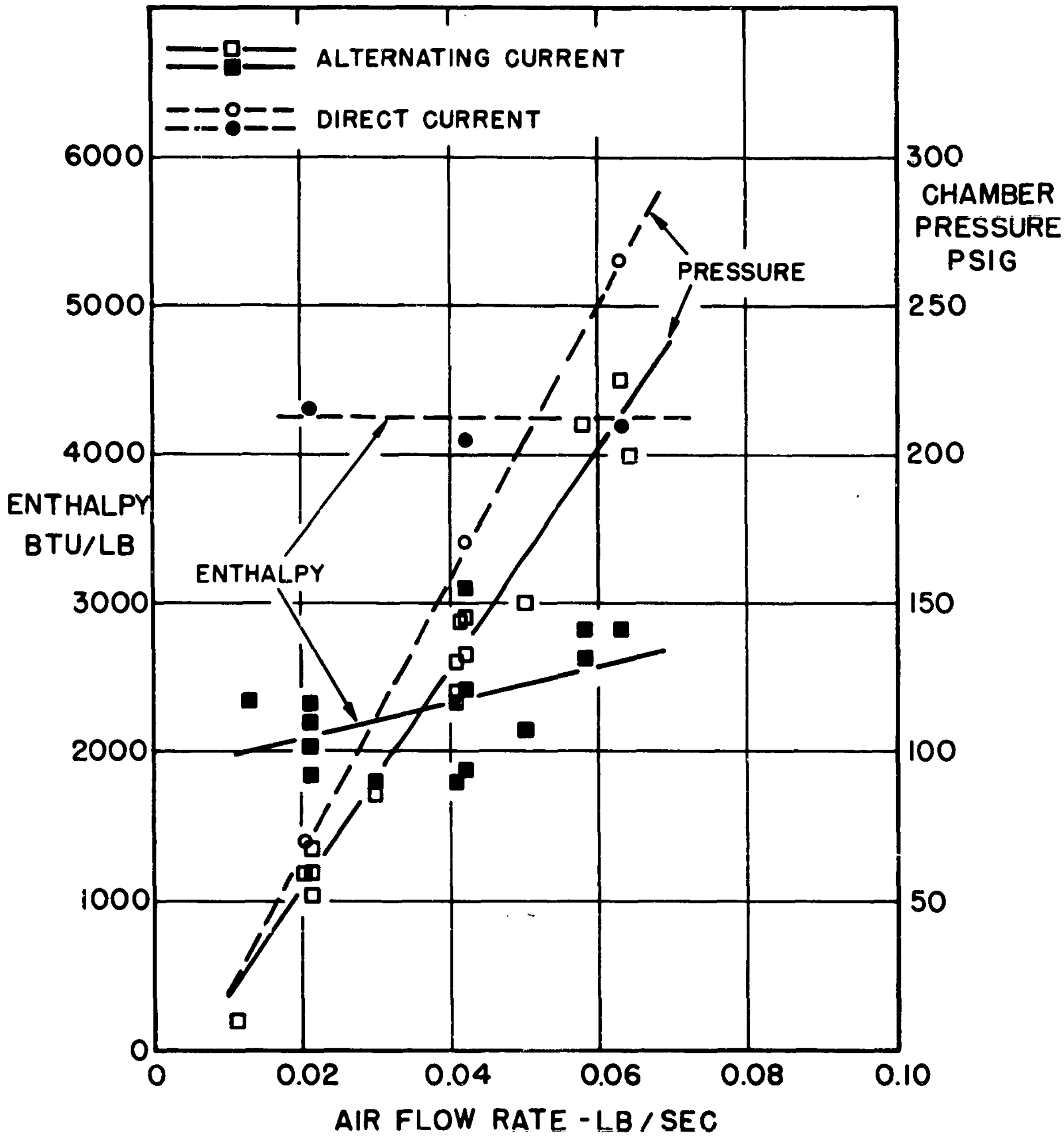


Figure 33. Model 119 Toroidal Arc Heater



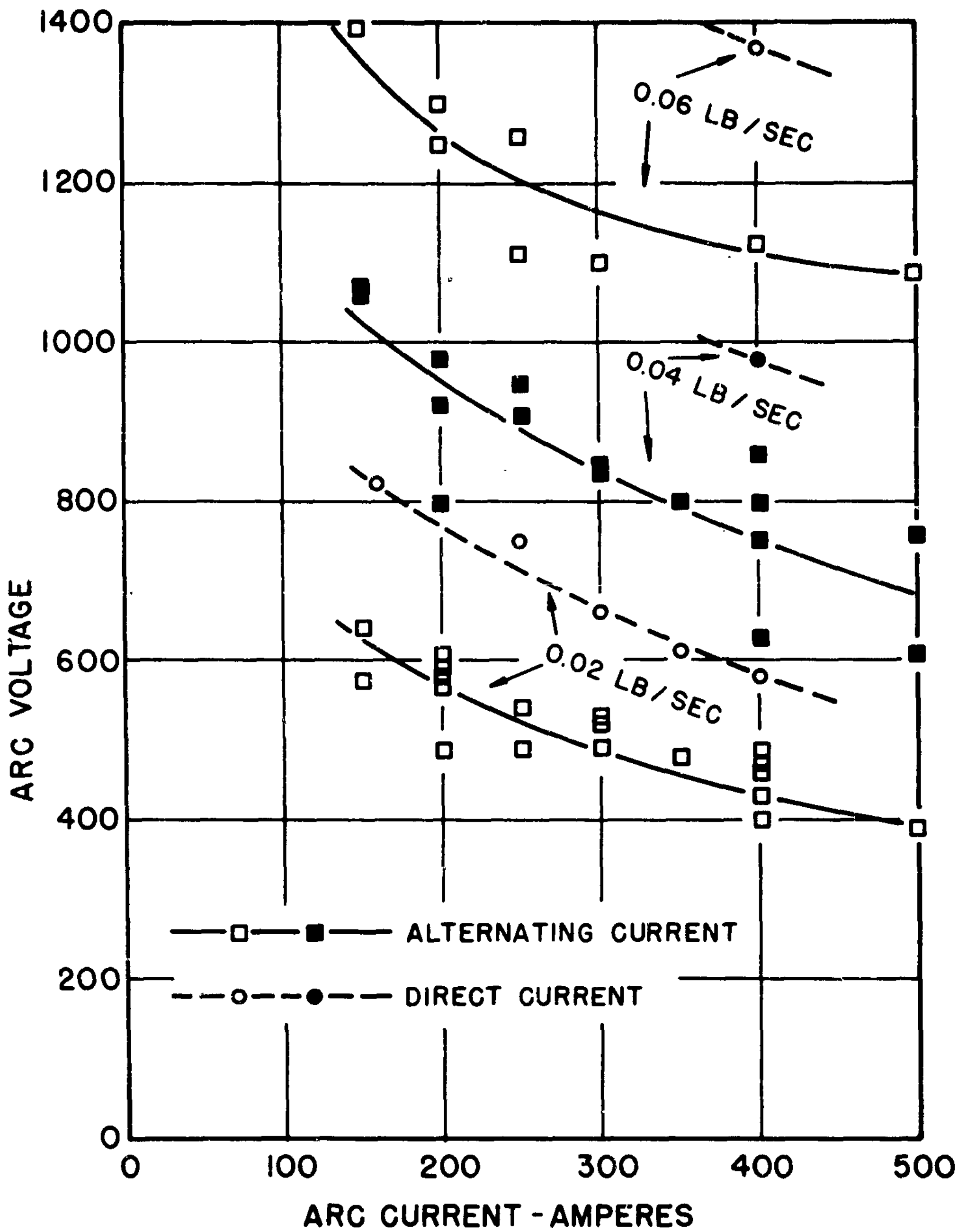
The data were obtained with a 1/4" diameter nozzle constriction and a 400 ampere rms arc current.

FIGURE 34. COMPARISON OF AC AND DC HEATER CHARACTERISTICS, MODEL 118, PART 1.



The data were obtained with a 1/4" diameter nozzle constriction and a 400 ampere rms arc current.

FIGURE 35. COMPARISON OF AC AND DC HEATER CHARACTERISTICS, MODEL 118, PART 2.



The data were obtained with a 1/4" diameter nozzle constriction.

FIGURE 36. COMPARISON OF AC AND DC HEATER CHARACTERISTICS, MODEL 118, PART 3.

Figure 37. High Voltage Arc Heater Voltage and Current Waveforms

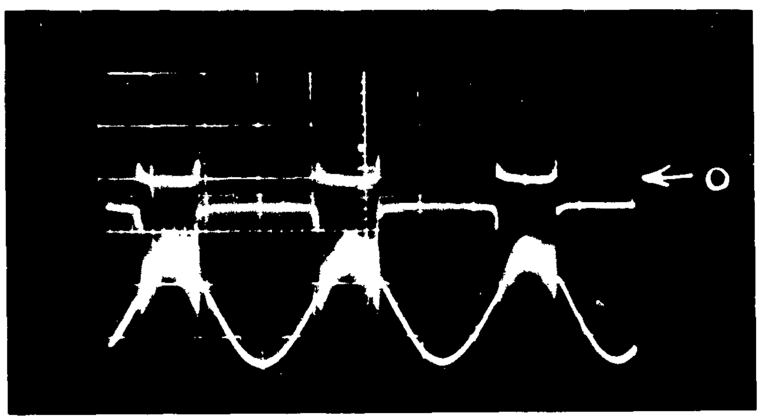


Figure 38. Direct Arc Heater Voltage and Current Waveforms

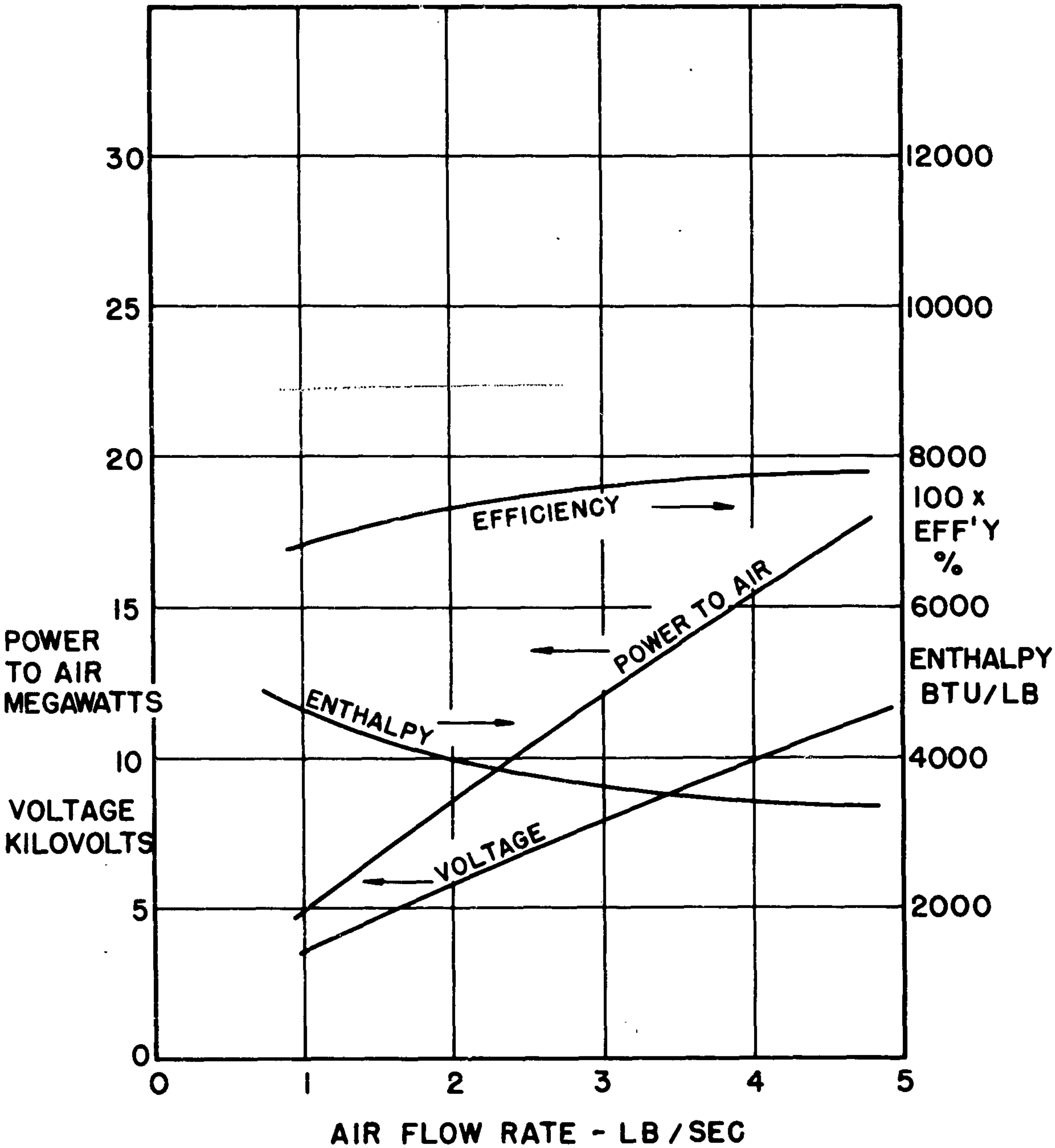


FIGURE 39. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (2000 AMP, UNCONSTRICTED)

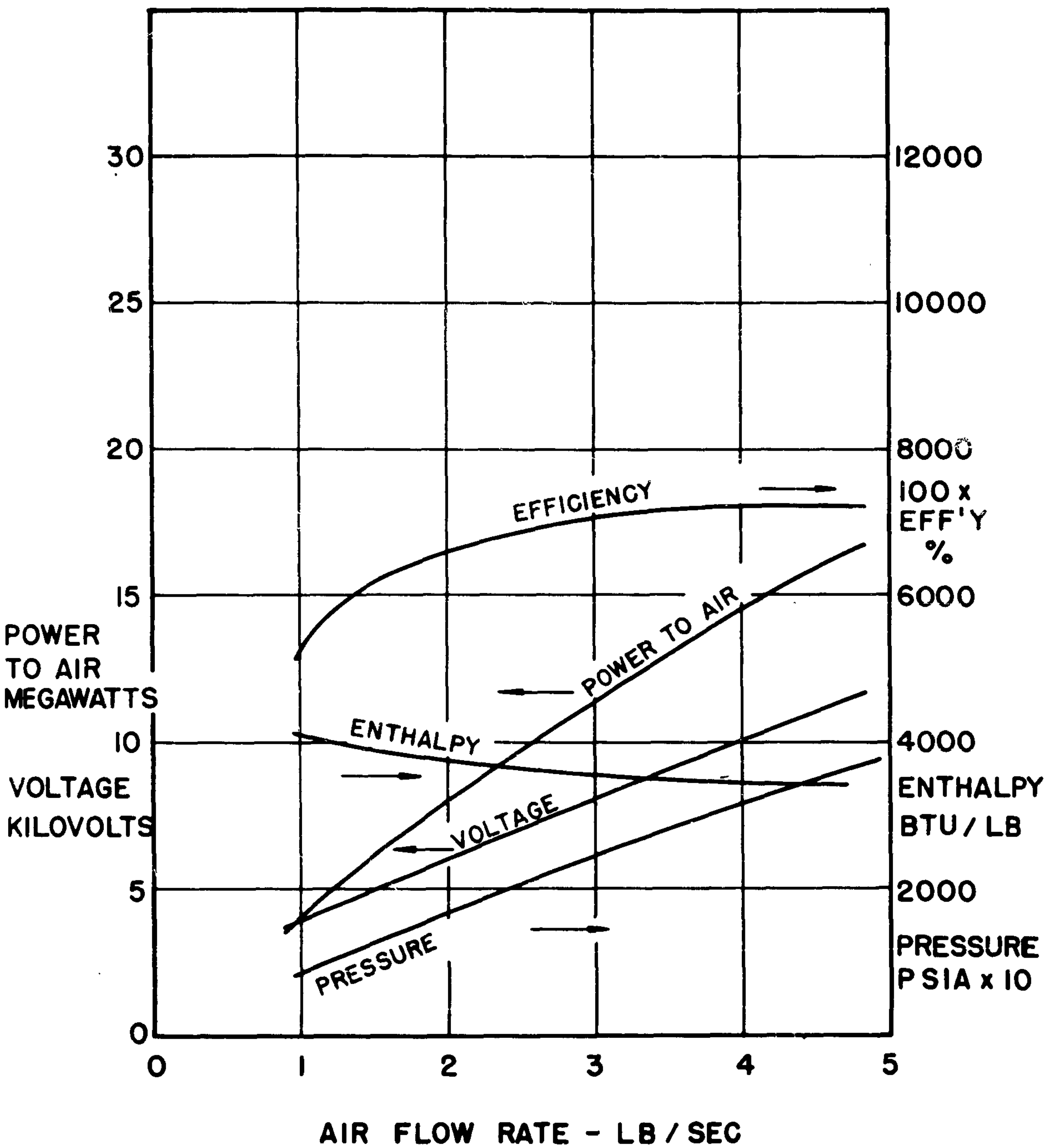


FIGURE 40. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (2000 AMP, 1.9" CONSTRICTION)

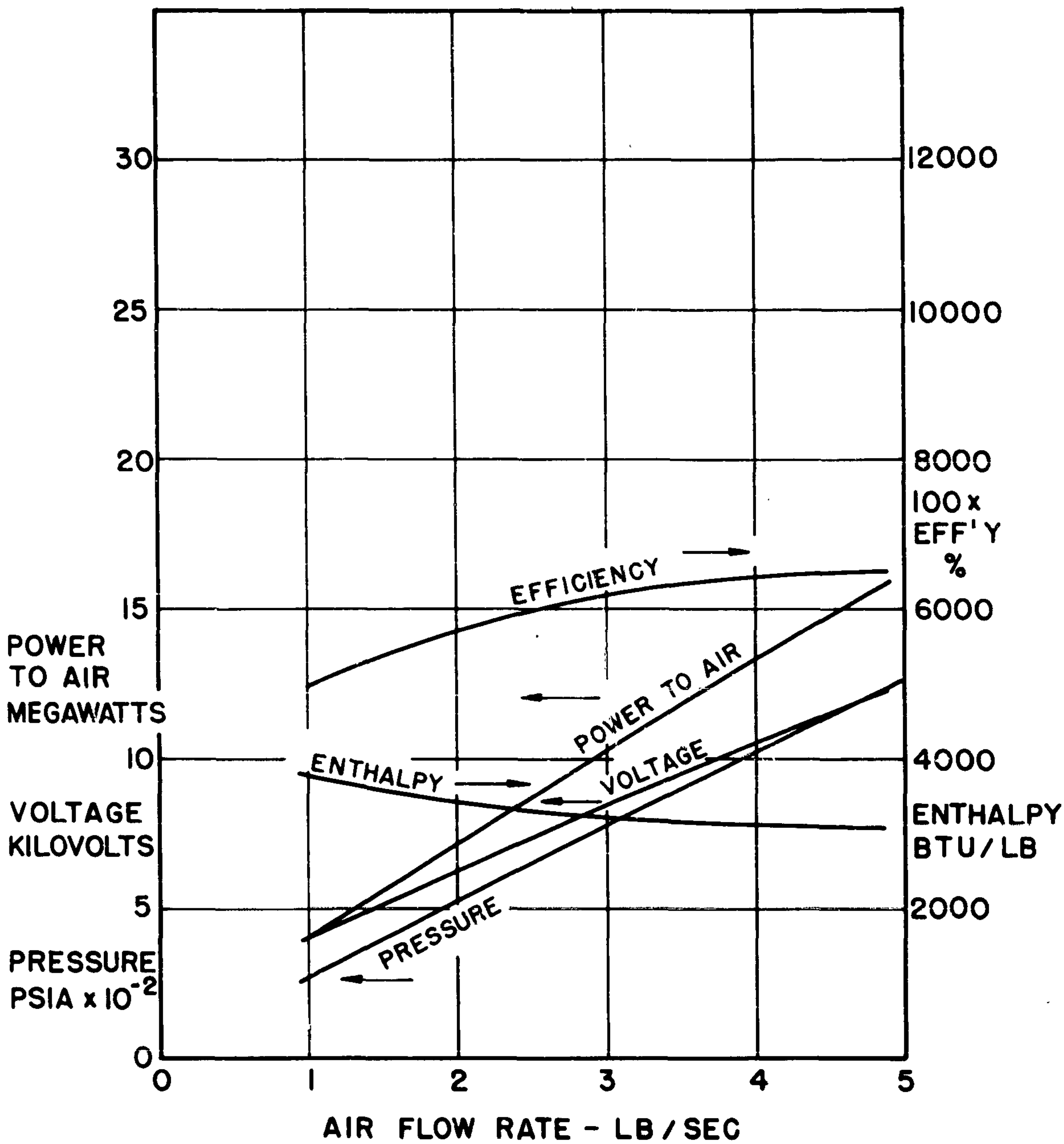


FIGURE 41. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (2000 AMP, 1" CONSTRICTION)

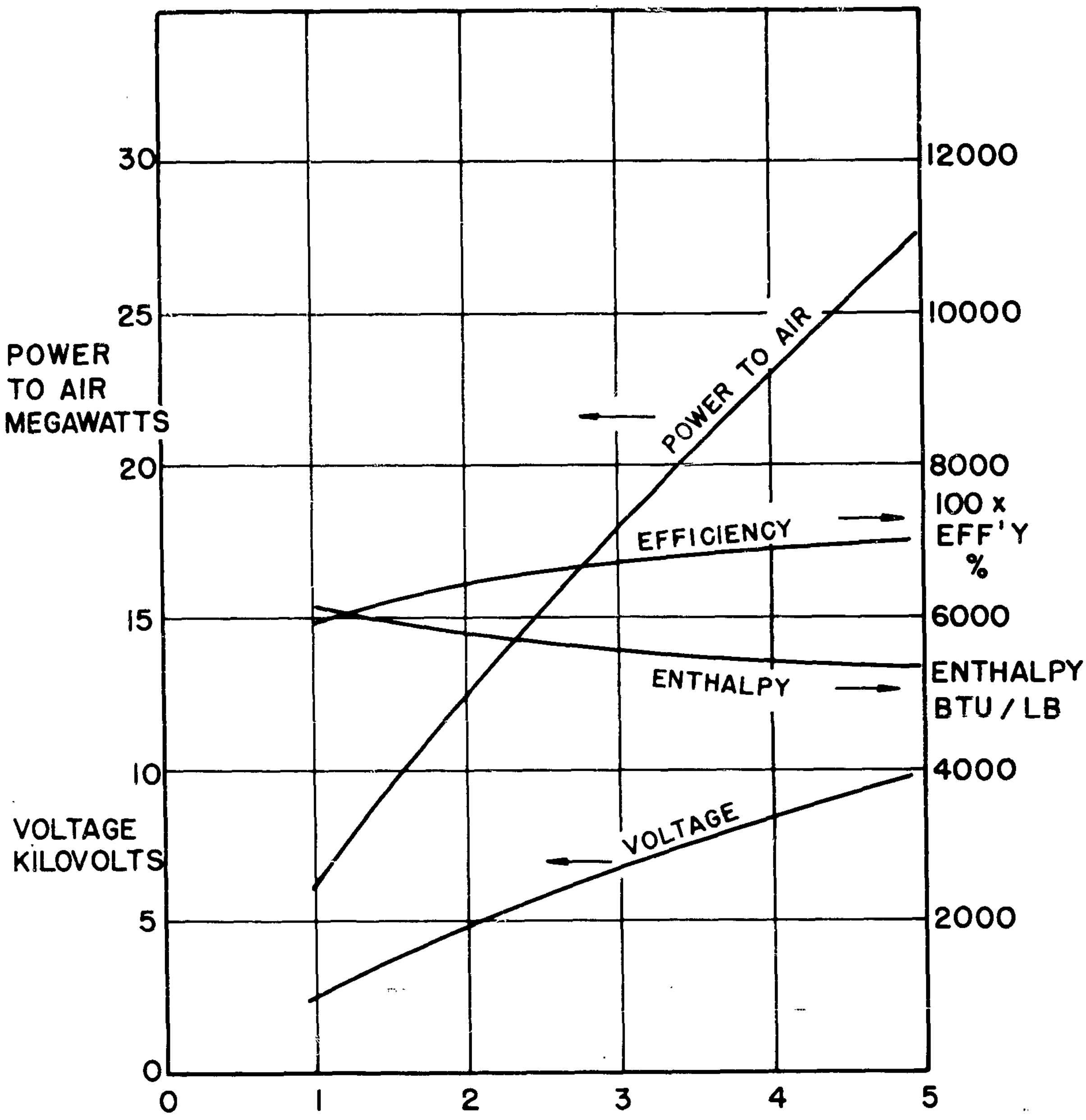


FIGURE 42. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (4000 AMP, UNCONSTRICTED)

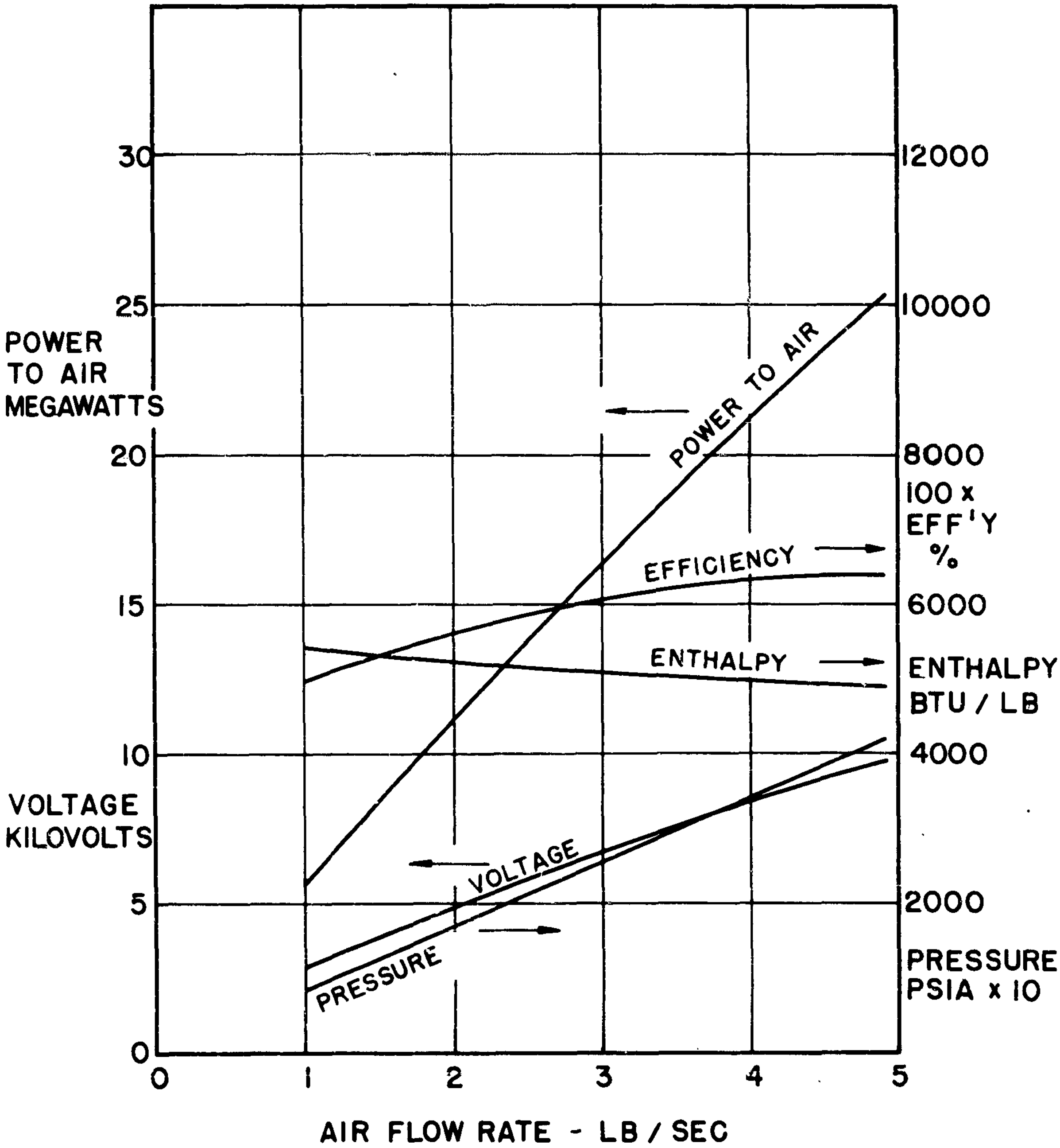


FIGURE 43. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (4000 AMP, 1.9" CONSTR.)

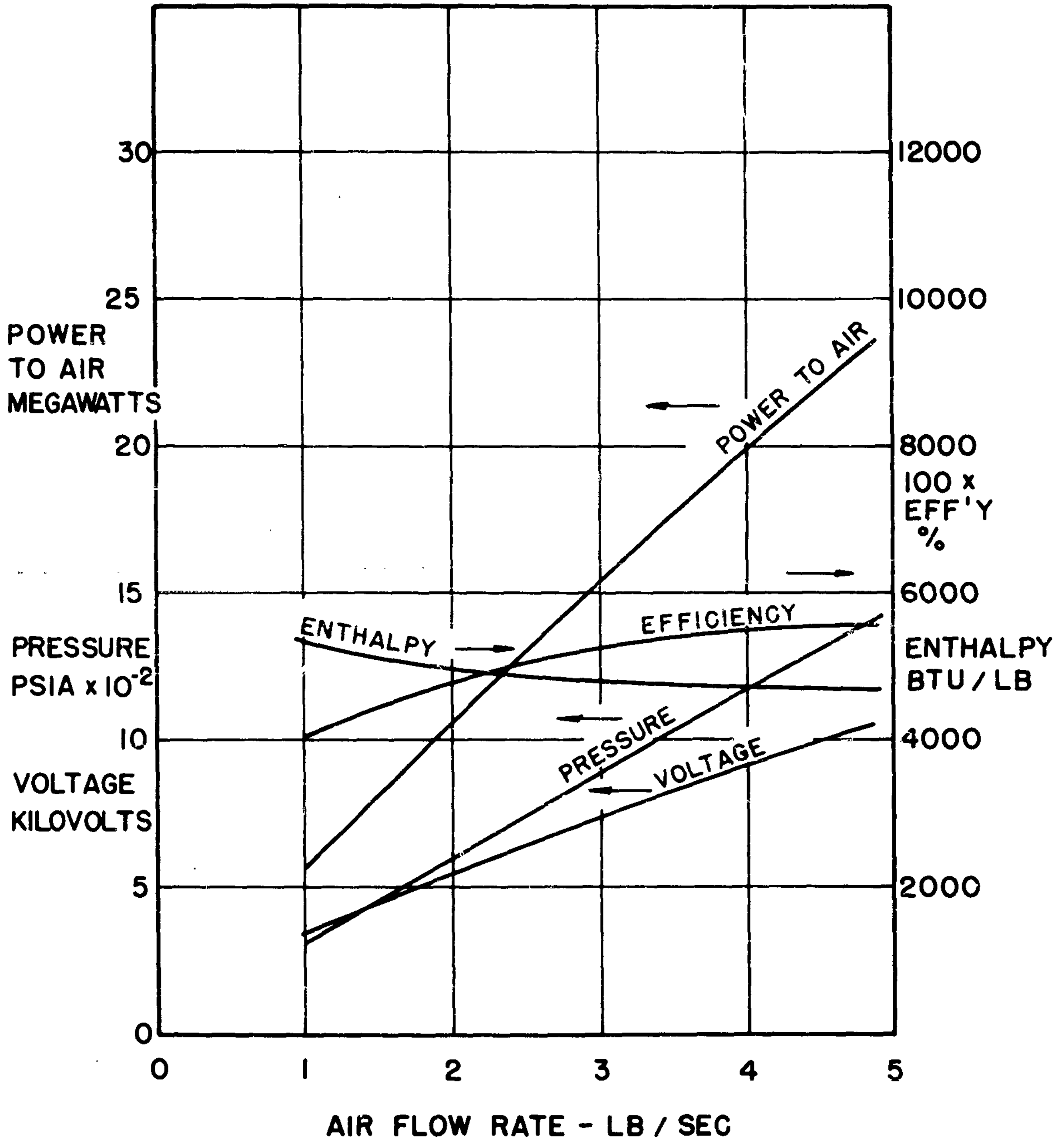


FIGURE 44. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (4000 AMP, 1" CONSTRICTION)

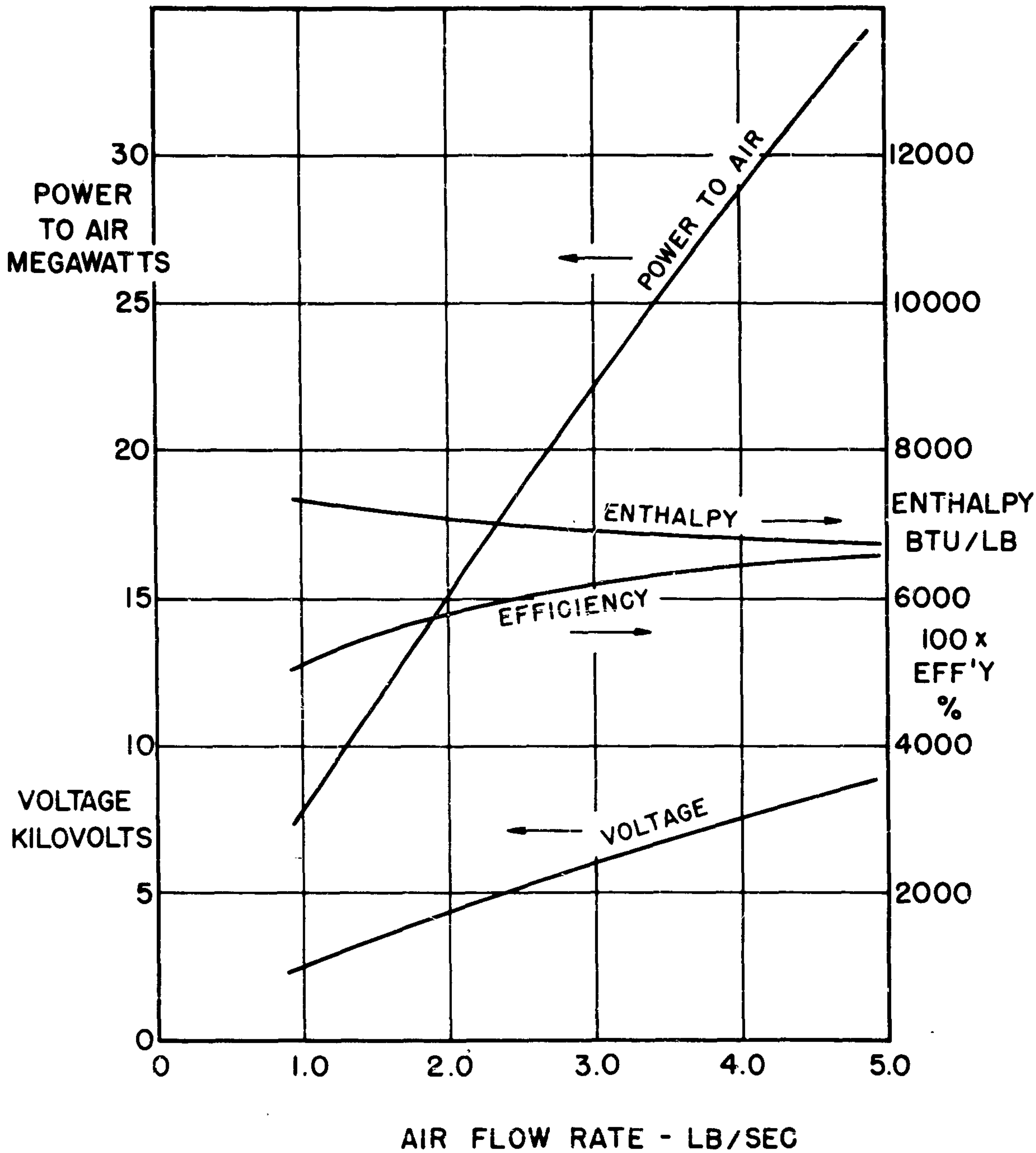


FIGURE 45. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (6000 AMP, UNCONSTRICTED)

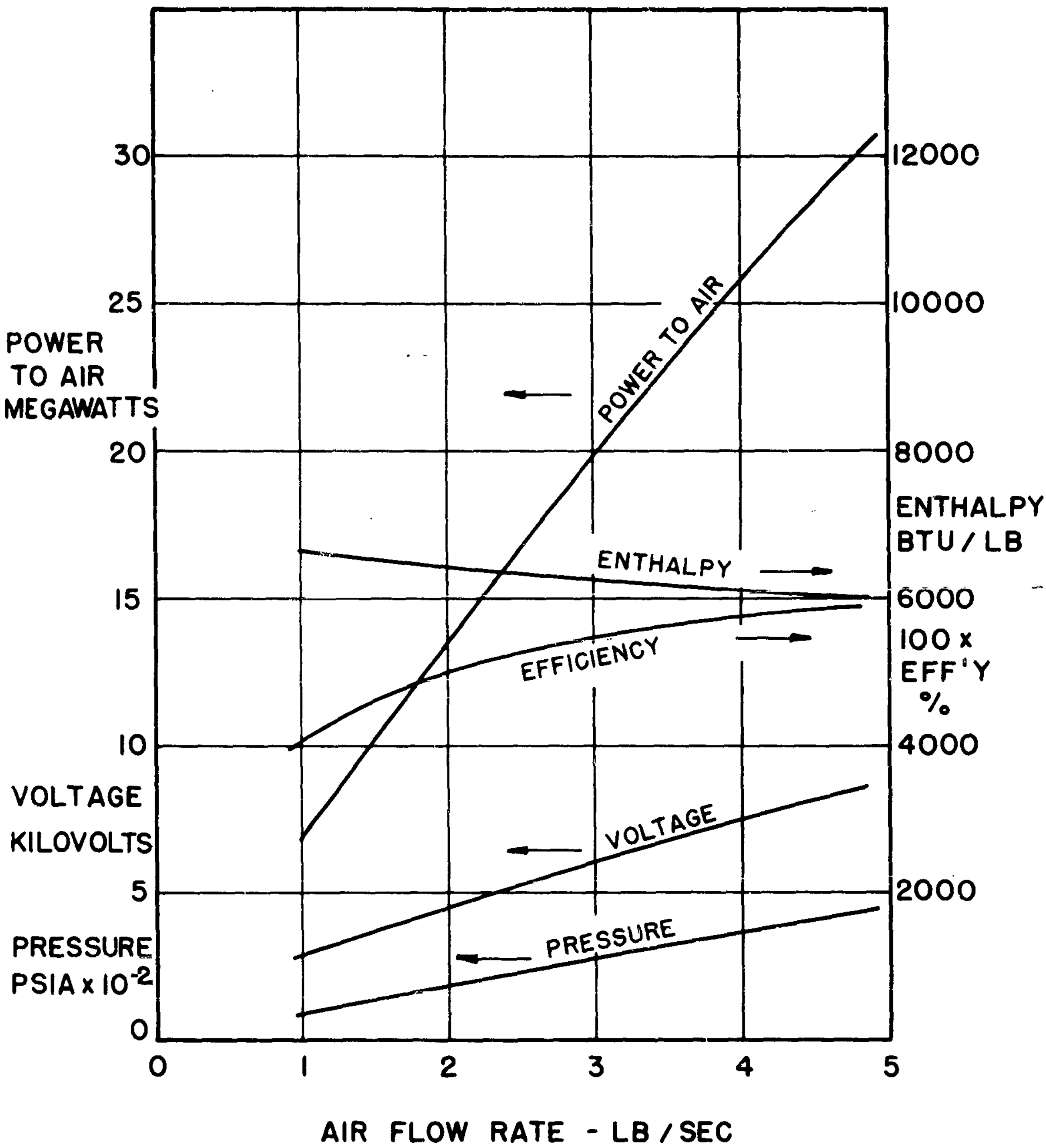


FIGURE 46. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (6000 AMP, 1.9" CONSTR.)

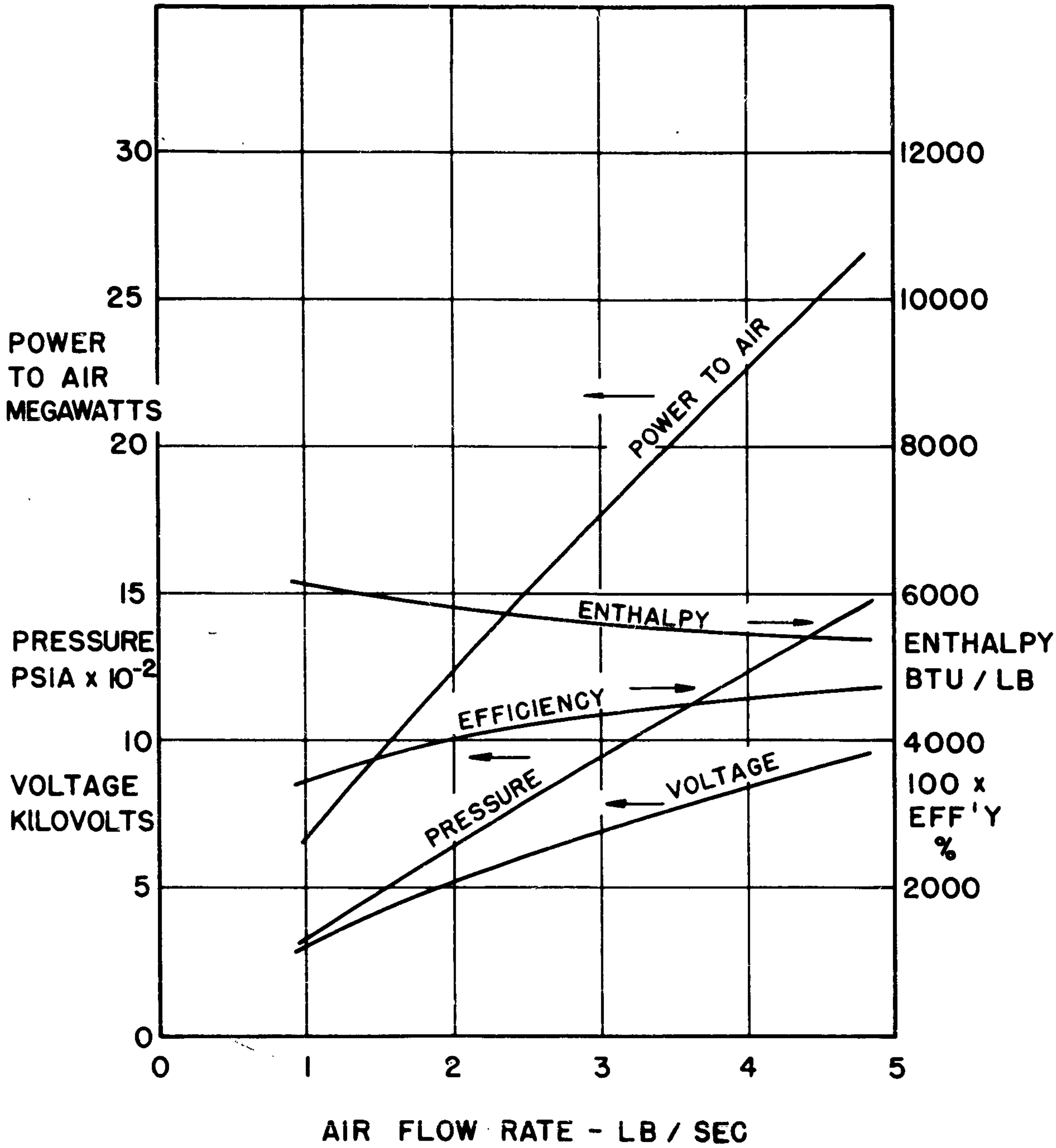


FIGURE 47. FORTY MEGAWATT HEATER PREDICTED PERFORMANCE (6000 AMP, 1" CONSTRICTION)

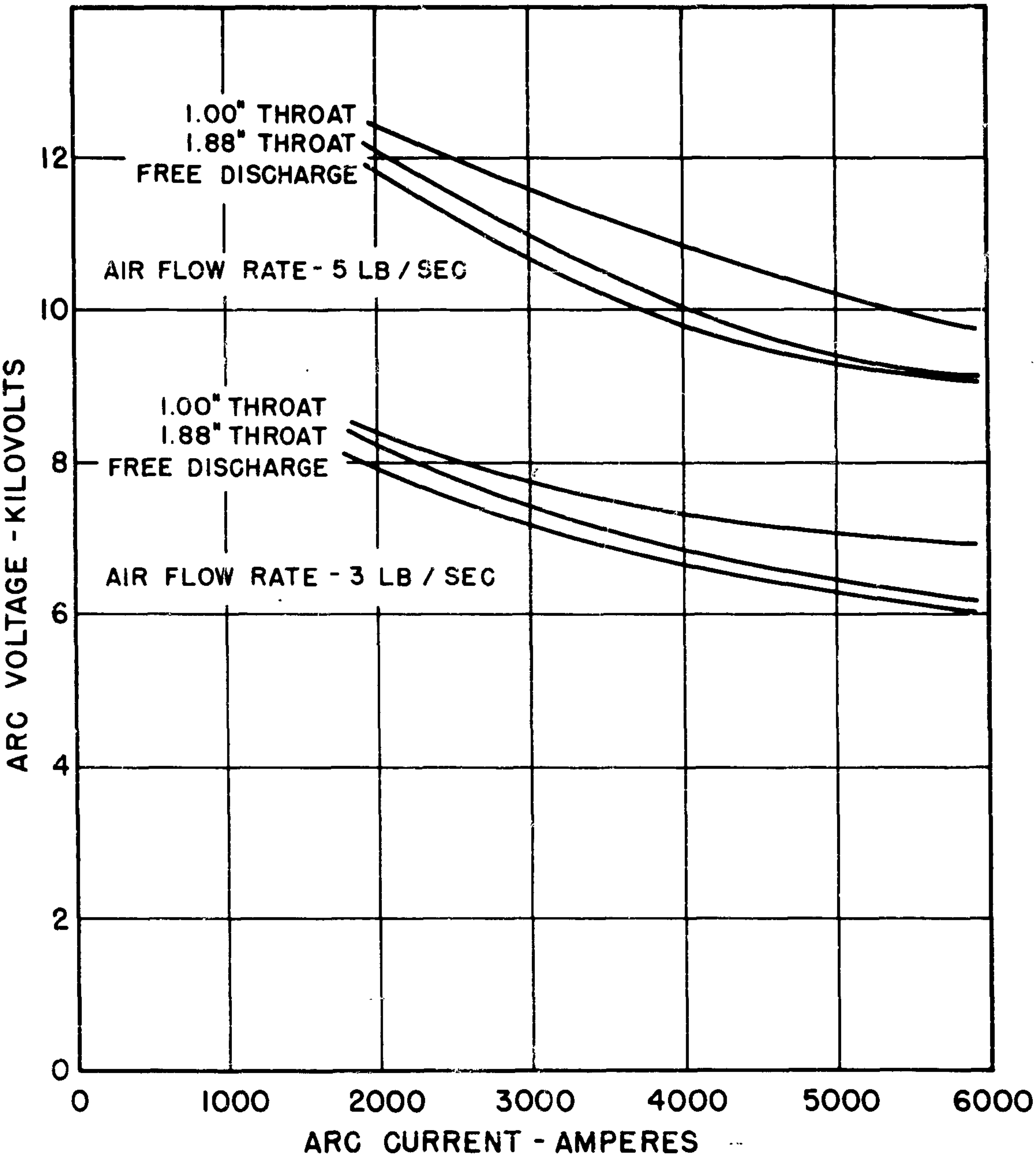


FIGURE 48. VOLTAGE-CURRENT CHARACTERISTICS OF FORTY MEGAWATT HEATER

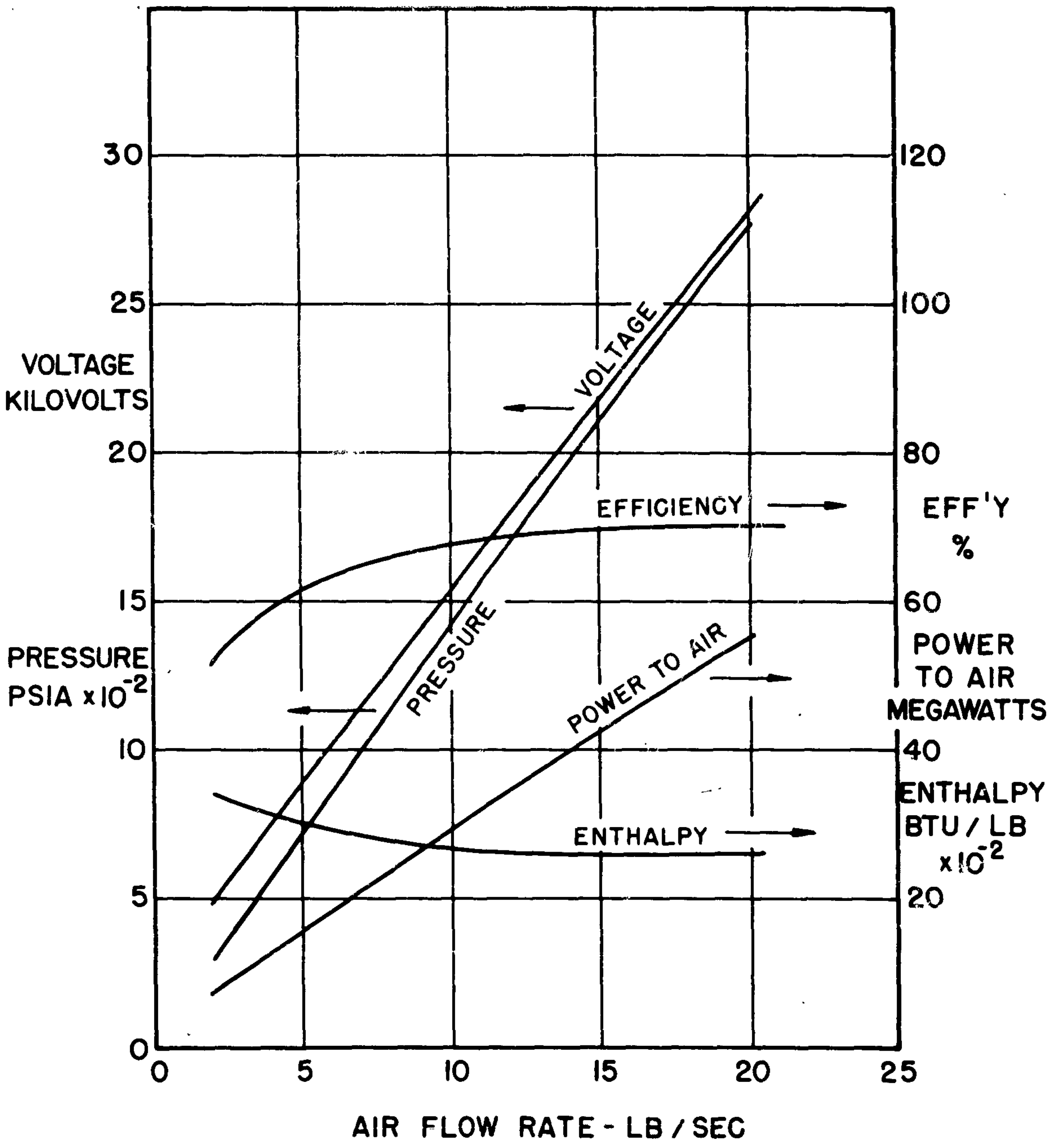


FIGURE 49. HUNDRED MEGAWATT HEATER PREDICTED PERFORMANCE (2800 AMP, 1.3" CONSTR.)

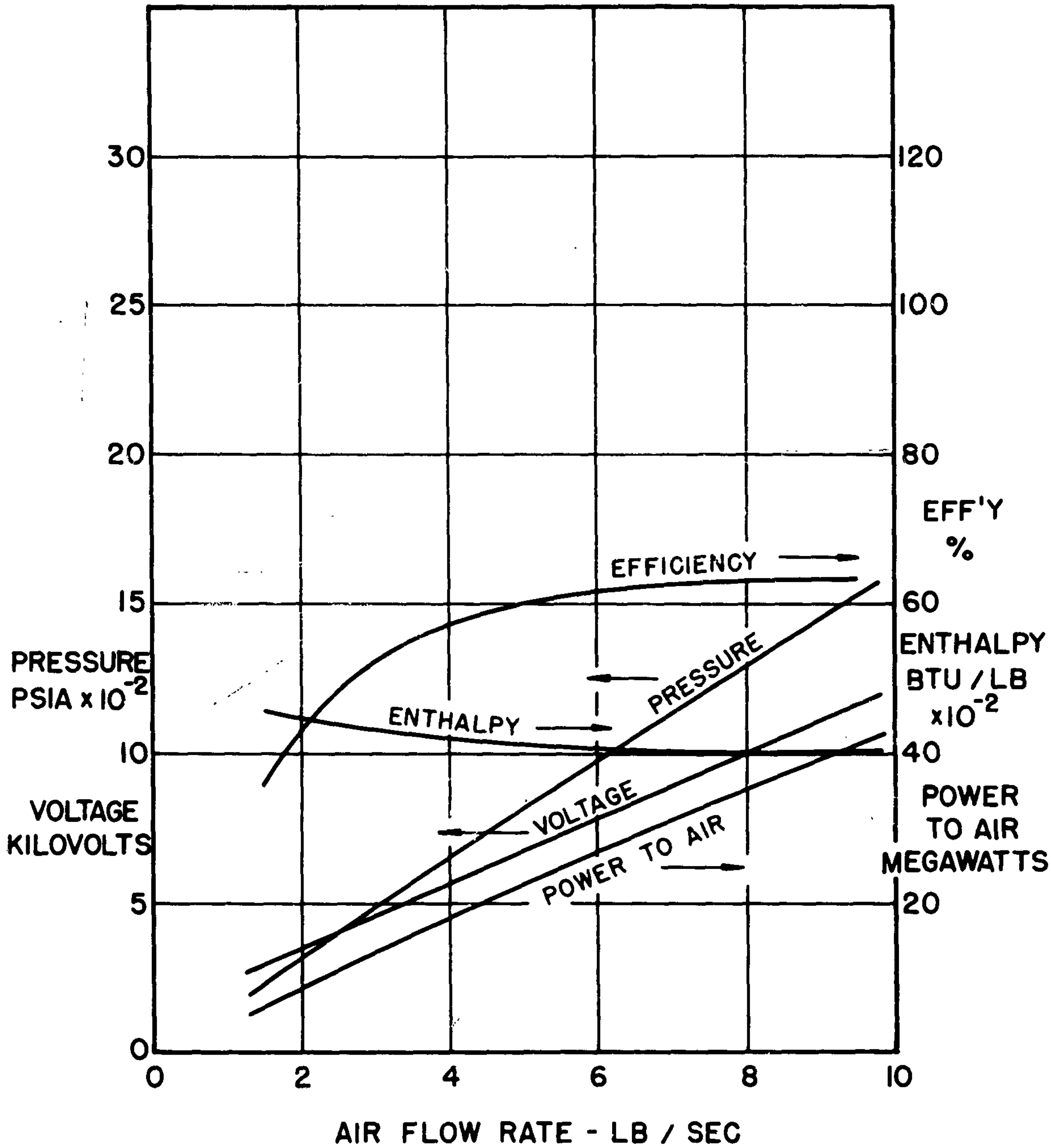


FIGURE 50. HUNDRED MEGAWATT HEATER PREDICTED PERFORMANCE (5600 AMP, 1.3" CONSTR.)

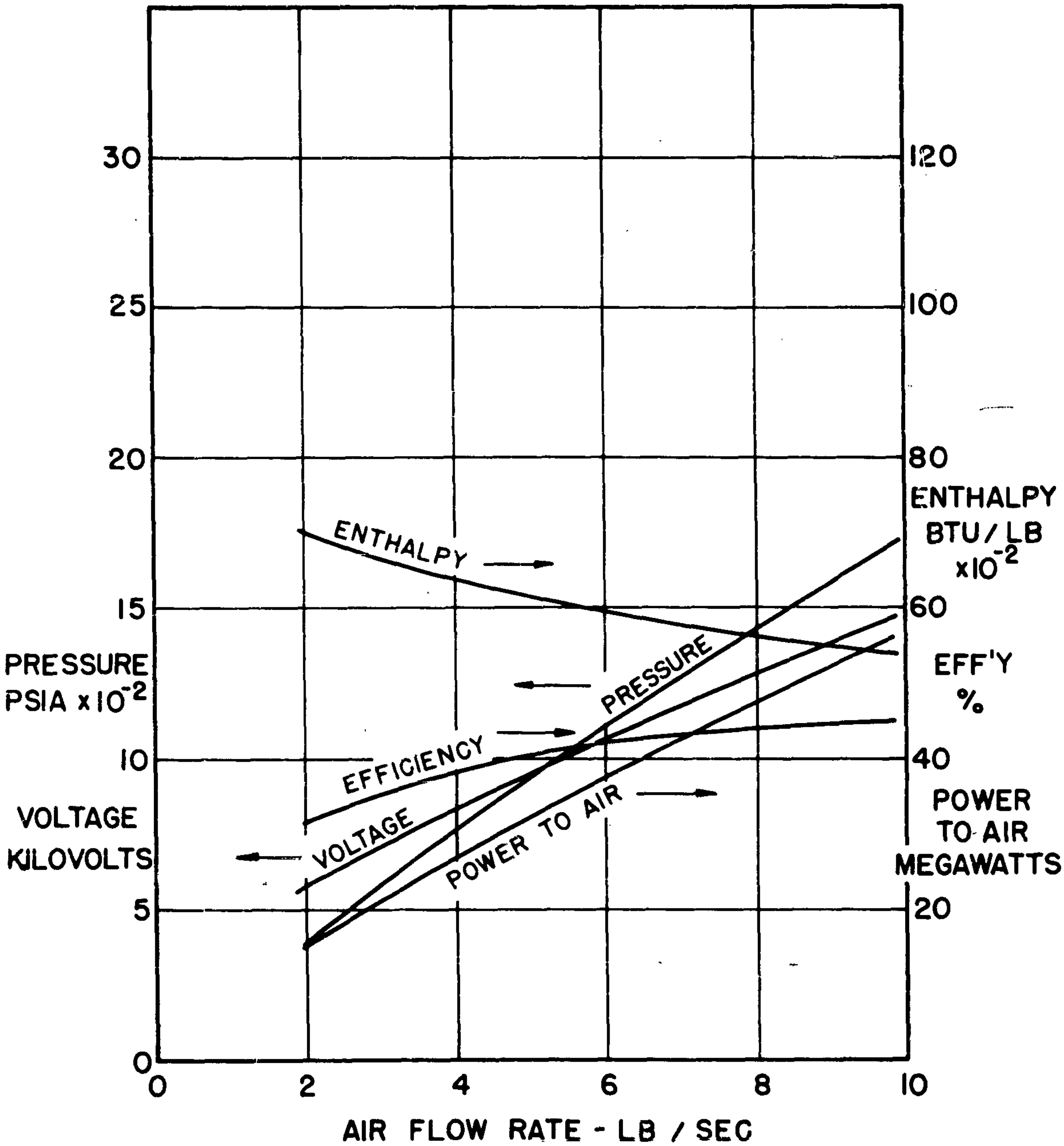


FIGURE 51. HUNDRED MEGAWATT HEATER PREDICTED PERFORMANCE (8400 AMP, 1.3" CONSTR.)

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3. Wind Tunnels, Hypersonic
4. Simulators, reentry

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